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INTEGRATION OF DECISION AIDS FOR STRIKE CAMPAIGN PLANNING.(U)

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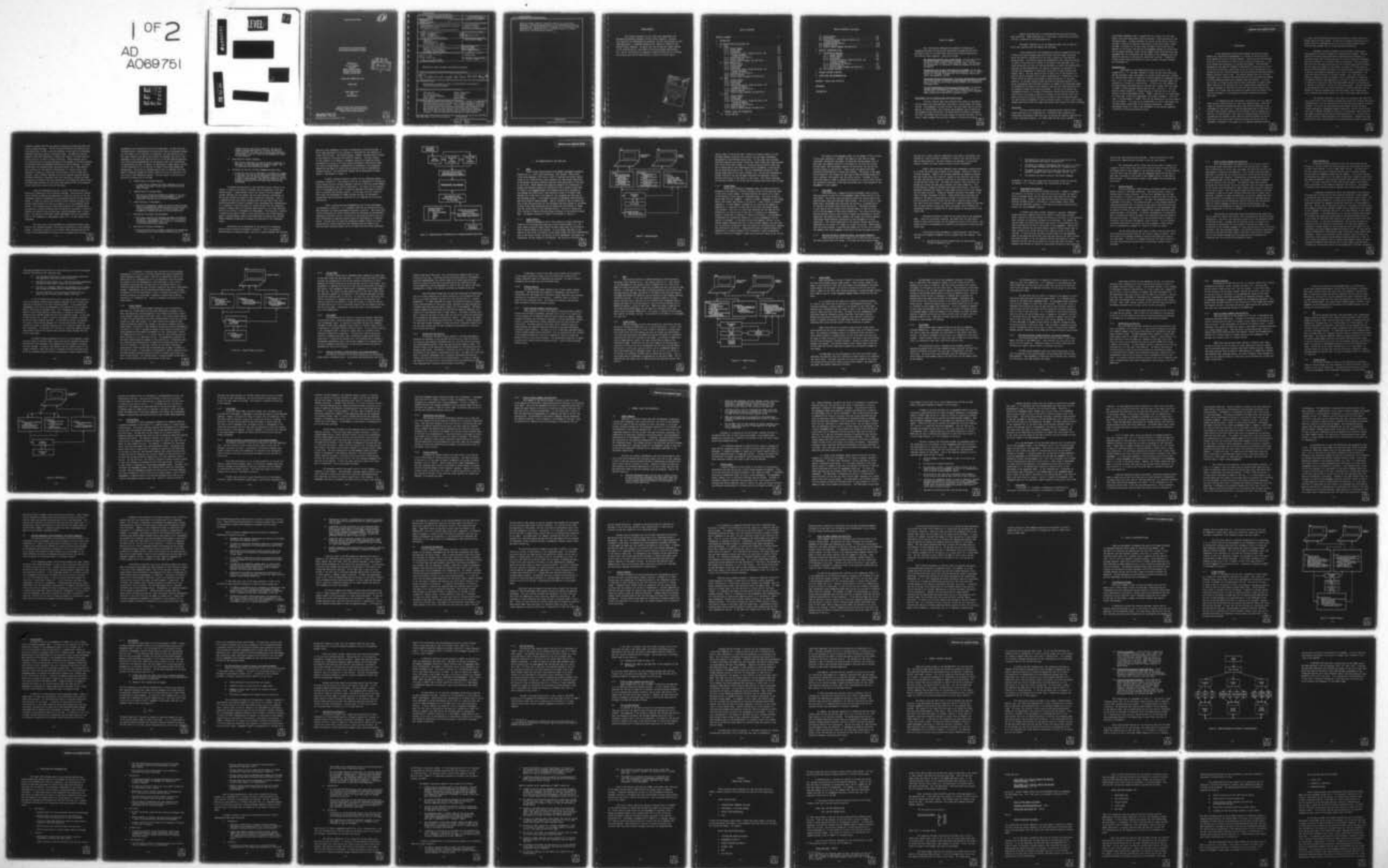

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INTEGRATION OF DECISION AIDS FOR STRIKE CAMPAIGN PLANNING

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17 May 1979

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This report examines the problem of integrating a number of independently developed decision aiding systems into a single comprehensive decision aid for strike campaign planning. The principal components considered for incorporation in the integrated system have been developed in the Operational Decision Aids Program of the Office of Naval Research. Four of the most relevant decision aids are described and discussed in detail. They are concerned with problems of route planning, cont.

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emission control planning, campaign planning, and strike time selection. Desirable characteristics of an integrated decision aid are discussed. Specifications are proposed for a first-phase implementation of an integrated aid as a system to assist in a broad range of air strike planning problems.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

EXECUTIVE SUMMARY

This investigation addresses the problem of formulating an integrated decision aid from several functionally related decision aids developed as part of the Operational Decision Aids program sponsored by the Office of Naval Research. These aids include:

<u>The Integrated Sciences Corp. Route Planner</u> - An aid that assists the decision maker in selecting the optimal air route from carrier to target through a radar detection field. The criterion for optimization is a function of detection probability and fuel consumption.

<u>The Analytics Air Strike Timing Decision Aid--ASTDA</u> - An aid that assists the decision maker in selecting the optimal time to launch a strike as a function of weather and force readiness factors that impact the engagement outcome.

<u>The Decision-Science Applications, Electronic Warfare Decision Aid-EWAR</u> An aid that assists in formulating electromagnetic emission control plans by balancing surveillance coverage benefits and information-given-away costs.

<u>The SRI International Strike Outcome Calculator-SOC</u> - An aid that estimates the consequences of alternate courses-of-action for a carrier based air strike campaign, using a deterministic engagement model covering both adversaries' operations plans.

Requirements for an Integrated Decision-Aiding System

The aids itemized above were analyzed with respect to the generic mission problem that they addressed, the specific process model that characterized the engagement (mission) actions, the value model used to quantify measures of effectiveness, the variables and parameters used in describing the systems and decision factors, the optimization and analysis procedures utilized, the methods used to display outputs to the decision maker, and the roles of human judgment and heuristics assumed in the decision process.

Several properties that an integrated decision aid should exhibit were identified. These properties are: consistency, flexibility, efficiency, validity, extendibility and understandability.

The mutual compatibility of the component models and the means by which they interface with one another are discussed.

It was decided that the integrated aid should be compatible with the diverse styles and strategies used by different decision makers and should permit the explicit incorporation of the user's expertise in the decision making process. Aid features should be implemented as user-controlled options in order to allow the aid to conform to the needs of the individual user. It should be possible to treat all data and processes as certain and deterministic according to the characteristics of specific situations or, optionally, to consider the consequences of statistical uncertainty in data estimates and process events. The user should be able to focus only on the features of a specific decision problem from a single perspective or, alternatively, configure the aid to address the problems of both adversaries in a war-game exercise. An optional operator-aided optimization technique based on a non-linear programming aglorithm might eventually be added to the integrated system for determining an optimal strike approach route and this technique might also be extended to other strike planning problems. The ability to examine the intermediate results in a process (intraprocess analysis) and to analyze the sensitivity of an outcome criterion of a process to the principal input variables (sensitivity analysis) should be available so that the decision maker can make reliable assignments of value to process results. Finally, the linkage between short-term action and longer term mission goals should be clearly displayed.

Conclusions

The four problem-specific aids discussed contain effective techniques applicable to an integrated aid. Integrating these separate aids necessitates considerable additional work to achieve the required compatibility in their overlapping domains. For ASTDA, EWAR and SOC to work together, a

consolidated engagement model is needed that will replace the individual models; the consolidated model should be operable in both deterministic and stochastic modes. A common procedure for valuing strike mission results is required to replace the separate value models of the Route Planner, ASTDA, and EWAR. Variables such as the flight altitude of the strike force on approach to the target, the duration of engagement between the strike force and the enemy interceptor force, and the damage levels sustained during the engagement must be incorporated into the models of the engagement and radar detection processes to improve their operational accuracy. Standardized display formats should be adopted for tables, graphs, and maps offered by the integrated aid.

Recommendations

Development of the integrated decision aid involves a two pronged effort -- a "top-down" approach in which the task force objectives and the consequent model requirements are further definitized and a "bottom-up" approach that defines a compatible interface between the component decision aids. As a first stage of integration, an integrated aid might support the planning for a single air strike mission. In such an aid, key elements of the Route Planner and ASTDA would be combined into a higher level aid known as SCAMP-1 (Strike Campaign Planning Decision Aid - Version 1). This aid would be upward compatible, allowing features of EWAR and SOC to be incorporated in future development efforts. SCAMP-1 would assist in a broad range of strike time, strike force complement, and target assignments. The first step in the development of SCAMP-1 would be the adaptation of existing process and value models. This step can be accomplished in a short time because the available models provide most of the necessary components. Subsequent development phases will require the development of new program components to achieve an efficient extendible system.

1. INTRODUCTION

In the Operational Decision Aids program, the Office of Naval Research has sponsored the development of a variety of decision aids for naval command and control decision problems. These aids have been designed to assist in the solution of various tactical decision problems that a task force command would encounter in a wartime environment. Aids have been developed for the specific problems of determining a flight path for an air strike force, selecting a launch time for an air strike, developing a comprehensive plan for a battle campaign, and constructing and analyzing electromagnetic emission control plans. Two general purpose aids have also been developed, one to construct and analyze decision tree structures and another to perform Bayesian updating and expected value calculations. At a more basic level, an extensive data base has been constructed to support experimental versions of the decision aids and a sophisticated superstructure has been developed to interface the user with the data base and the aids. Together, all of these aids and supporting systems offer assistance to the task force command in a wide range of decisions concerning task force operations.

In contemplating the simultaneous installation of all or some of these decision aiding systems in a task force command center, there are a number of important considerations which have not been addressed in the development of any single aid. These considerations bear on the issue of how the aiding systems interface with one another, both in concept and in practice. On the practical side, there are questions about how the user accomplishes the transfer of data from one system to another in cases in which two or more aids perform related functions and how the user can implement a component of one system (e.g., a Bayesian updating processor

or a multi-variate optimizing algorithm) to perform a related function for another decision aiding system. The lack of an adequate interface can completely block any complementary use of distinct systems despite obvious interrelations between the real situations being represented.

Conceptual interface problems can arise from an inconsistent interpretation of similar concepts by different aiding systems. The same real-world variable might be defined or quantified very differently in separate systems, thus requiring the user to enter the same data repeatedly, each time according to a different arbitrary convention. Distinct systems that deal with the same process may focus on different descriptive variables for the inputs and outputs of the process, and they will almost certainly employ different mathematical models for the same process. Different levels of details and degrees of aggregation are likely to be represented in the input and output variables of different systems. Thus, the lack of an effective conceptual interface between a set of functionally related aids can generate confusion and aggravation on the part of the user because he is required to supply more input data than appears necessary and because he is pressed to interpret a variety of conflicting outputs. Interface problems at the conceptual level can also be expected to interact adversely with any mechanical interface problems that are also present, thus disposing the user to operate each aiding system as if none of the others were available.

The research described in this report has focused on the identification and solution of the interface problems that would arise from the collective implementation of the four ODA decision aids which deal with specific tactical problems. The aids to be interfaced with one another include the Route Planner developed by Integrated Sciences Corporation, the Air Strike Timing Decision Aid (ASTDA) developed by Analytics, the Electronic Warfare Decision Aid (EWAR) developed by Decision-Science Applications, Inc., and the Strike Outcome Calculator (SOC) developed by SRI International. Attention has been restricted to these problem-specific aids because they pose more substantial

interface problems than the more general systems and because they deal with clearly related processes. The SOC simulates offensive and defensive task force operations in order to provide estimates of the results of protracted campaigns directed by precise contingency plans. The EWAR aid simulates defensive task force operations to predict the results of various emission control policies in specific threat situations. ASTDA simulates single air strike missions to provide estimates of the outcomes of missions launched at different times and manageable evaluations of those outcomes. The Route Planner does not incorporate any simulation process, but it does employ a value function for the potential effectiveness of a strike mission that approaches a target by a particular route through a field of enemy radar stations. Major interface problems can thus be expected regarding the SOC and EWAR simulations of defensive task force operations, the SOC and ASTDA simulations of offensive task force operations, and between the Route Planner and ASTDA identifications of the factors that determine the strike potential of the strike force upon arriving at the target.

There are undoubtedly many ways in which the ODA aids could be effectively integrated to avoid interface problems. Each particular problem can be resolved by adopting the mechanism or concept of any one aid for the integrated system or by developing a new compromise feature for the combined system. In order to resolve just the more serious interface problems, substantial modifications will have to be made to all of the component aiding systems. The ultimate extent of these modifications will be determined by the particular interface problems that are addressed, the manner in which the problems are resolved, and any additional system development that is undertaken. The subject of additional system development should be considered in light of the incomplete or experimental status of all of the systems to be integrated.

The first step in the development of an integrated aiding system from all four prototype systems is the careful examination of each component system. Accordingly, Section 2 of this report offers detailed descriptions of each of the problem-specific decision aids as gleaned from available

documentation and conversation with the aid developers. We must note that the observations, interpretations and conclusions that are expressed throughout this report, and in Section 2 in particular, are the responsibility of the report authors alone and do not necessarily represent the views of the developers of the individual decision aids or of the ODA steering committee. Since the existing documentation for the decision aids varies considerably in organization and level of detail, we constructed a single general outline for the discussion of all of the aids in order to facilitate comparisons between them. The outline is designed specifically to highlight the fundamental differences between the aiding systems which must be resolved as the first step of the integration process. The main points in the outline of decision aid features are as follows:

- Identification of target problems.

  -- In what type of situation and what timeframe is the aid designed to be used? On what types of decision options does it focus?

- Identification of process models.

  -- Does the aid incorporate mathematical models of any real-world processes such as military engagements or repair operations? How are any such models implemented?

- Identification of value models.

  -- Does the aid determine a numerical value for each decision option to represent the overall desirability of that option in terms of the objectives of the decision maker? What mathematical formulae are used for such calculations?

- Description of variables and parameters.

  -- What input variables and parameter estimates are required by the aid? What outputs are offered? How are decision alternatives represented? How, if at all, is uncertainty in estimated quantities represented?

- Description of analysis procedures.

  -- Does the aid provide an automatic procedure for determining a configuration of input variables which results in an

optimal value of some output criterion? Can the user examine isolated sensitivities of output variables to input variables? Are other auxiliary analysis techniques incorporated in the aid? What are the mathematical bases of such analyses?

- Description of display features.

  -- What display techniques are used to convey information to the user? Is data displayed in tables or graphs? How is statistical distribution data coded?

- Discussion of the role of human judgment and heuristics.

  -- In what way does the aid complement or preempt the judgment of the user? Can the aid be used equally effectively with a variety of decision making strategies or does it dictate a single, fixed strategy? Does the aid require the user to provide any estimates that he cannot make reliably and confidently?

Following the description of the individual aids in Section 2, we discuss in Section 3 the specific problems that are addressed in the integration process. These problems concern the issues of how the component systems interface with one another and also some important shortcomings in the current systems with regard to their operational objectives. While it is appropriate that the current prototype decision aids should have incorporated some simplifications to expedite their development and implementation, it is important to avoid building such simplifications into the integrated system in a manner that will hide the simplifications or will make them more difficult to rectify in subsequent aid development. The discussion in Section 3 identifies the specific areas in which modifications and further developments of system features should be considered both to improve the interface between component systems and to enhance the usefulness of the integrated system.

Descriptions of two approaches to the design of an integrated decision aiding system are presented in Section 4. The first approach, characterized as a bottom-up design, consists of piecing together the available

decision aiding components to create an harmoniously functioning system. A first stage application of this approach is described for the planning of a single strike mission. The second approach, termed a top-down design, focuses on the problem of structuring the decision situation. The basic concept of this approach is to conduct a systematic analysis of objectives before proceeding to an analysis of action options available to the decision maker. This type of system design is appropriate for expansion of the integrated system from the domain of single strike planning to that of comprehensive campaign planning. The relationship between the two approaches to system design is represented in Figure 1-1.

A general software structure suitable for the integrated system is presented in Section 5. The structure calls for the separation of the decision aiding system into the distinct component functions of data base establishment, problem specification, and solution description. The object of this organization is to segregate data that is relatively permanent and general from data that is transient and situation specific. At the same time this structure facilitates the development of common software routines for performing related data input and analysis functions for all component decision aiding applications.

Finally, conclusions and recommendations for further development are presented in Section 6. It is suggested that both the bottom-up and top-down approaches to system development be pursued in parallel. New display and analysis techniques for strike planning should be developed and experimentally evaluated as one effort while a structure for analyzing task force goals and their relationship to decision options should be investigated as a separate effort. The end result of these two approaches together should be an integrated decision aiding system that both addresses the real needs of the decision maker and makes optimal use of available decision aiding technology.

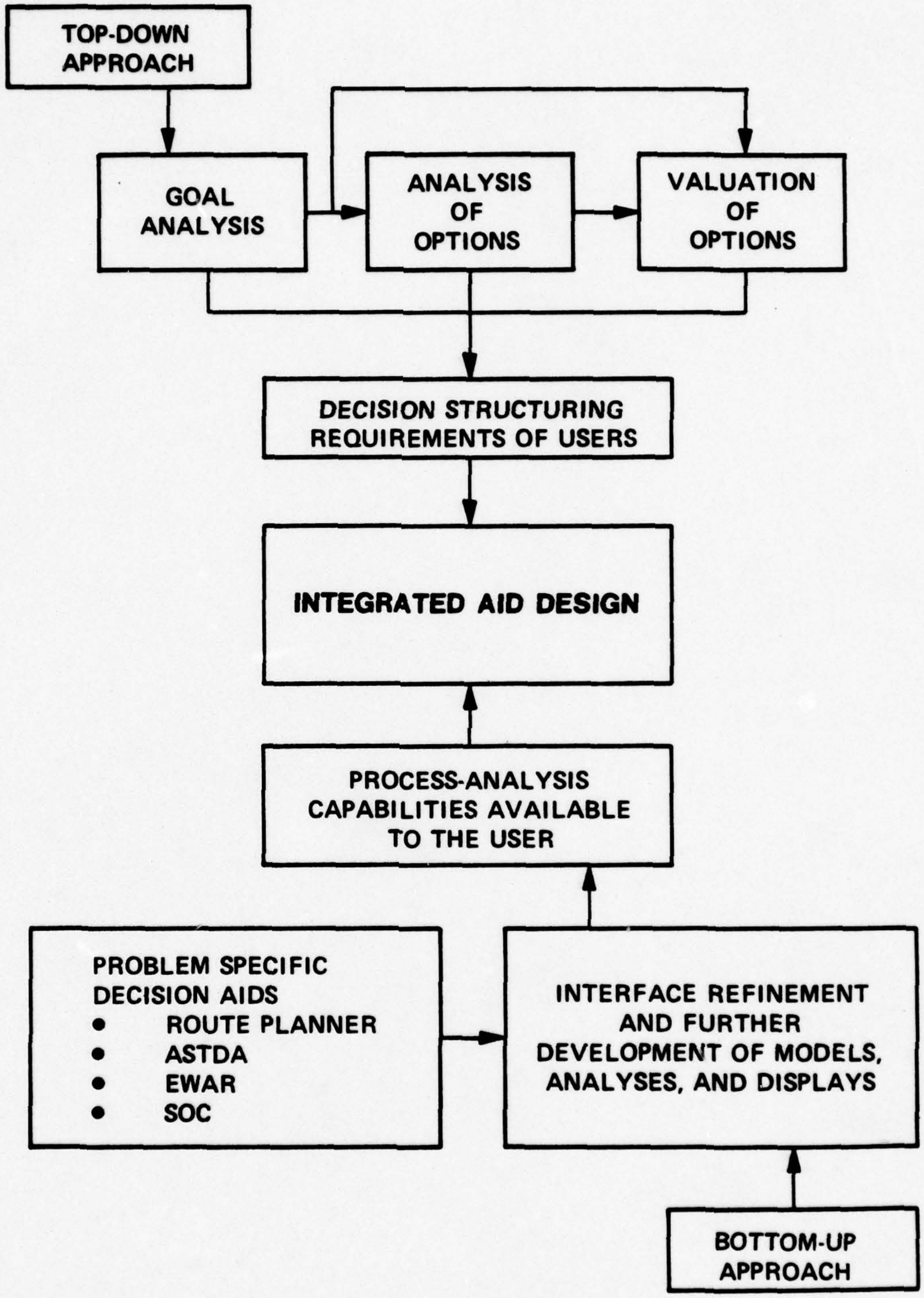

Figure 1-1. General Approach to Development of an Integrated Decision-Aiding System

2. THE PROBLEM-SPECIFIC DECISION AIDS

2.1 ASTDA

The Air Strike Timing Decision Aid (ASTDA) developed by Analytics (Epstein et. al., 1977; Glenn and Zachary, 1978; Epstein, 1978) assists a Task Force Commander (TFC) and his staff in choosing the optimal time to launch an air strike mission, given uncertain and time-varying predictions of the weather and force readiness conditions that would obtain at the time of the strike. ASTDA combines user-supplied probabilistic predictions of weather and readiness states with information from an extensive data base as inputs to an engagement model which produces statistical estimates of the outcomes that would result from launching strikes at different times. Outcomes are in the form of unit-specific loss estimates for each type of own and enemy system. A value model provides an aggregated mission-achievement score based on these outcomes. Special features of the aid enable the user to test the sensitivity of loss estimates and value outputs to variations in each of the input predictions and to examine the distribution of losses over the various parts of the simulated mission. The aid is interactive, with a variety of tabular and color graphic displays of the input and output data. The general structure of ASTDA is represented in Figure 2-1.

2.1.1 Target Problem

ASTDA was designed to aid in the situation in which a decision to launch an air strike has been made and a strike launch window (i.e., the total range of possible launch times) has been established, but the precise time to launch remains to be resolved. It also assumes that many of the details of the strike, in addition to the launch window, have been predetermined, such as the type of strike, the optimal aircraft complement, the weapon configurations, and the targets to be attacked. The results of launching at

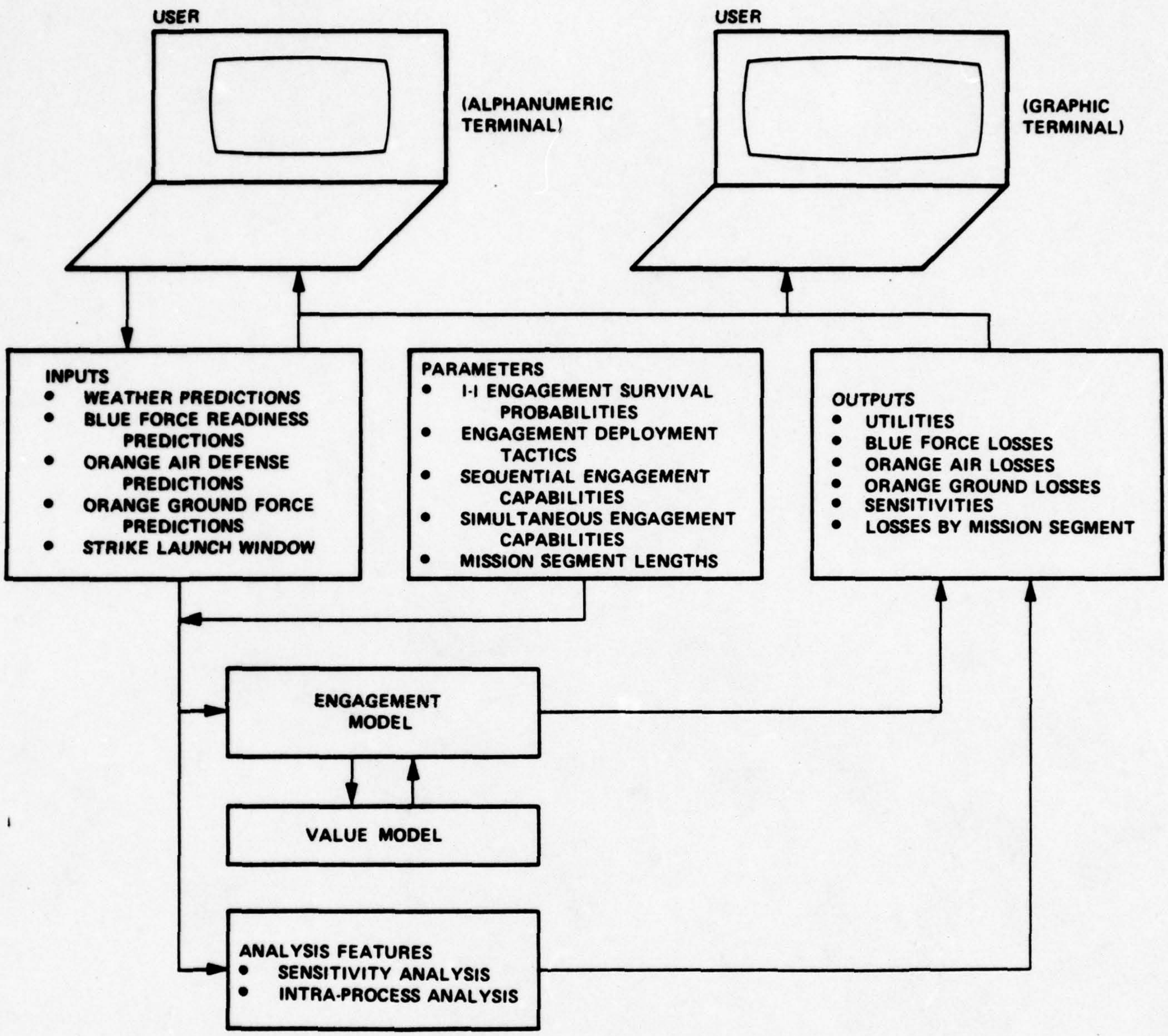

Figure 2-1. ASTDA Structure

various times in the strike launch window are affected primarily by the different weather conditions and states of own and enemy preparedness encountered at the different launch times. To the extent that extremely different conditions may prevail during the launch window than those expected when the Op Orders were formed, it is possible the the decision maker may opt to change some of the predetermined mission parameters or even decide not to launch the strike at all. The aid incorporates arbitrarily fine-grained predictions of the input variables (e.g., hour-by-hour estimates of weather conditions and own and enemy readiness) and generates similarly detailed predictions of the results of the strike. The primary timeframe for the use of ASTDA is the 24 hour period preceding the strike launch window.

2.1.2 Process Model

ASTDA uses a stochastic engagement model to produce statistical estimates of the results of strikes launched at each of the specified times in the strike launch window. The model predicts the results of a single carrier-based air strike against a defended target. The strike mission is sub-divided into four segments -- ingress to target, engagement at the target, egress from target, and landing at the carrier -- each of which is modeled separately. In each segment, a probability of surviving the segment is computed for a single unit of each type of Blue (own) and Orange (enemy) force element. Each unit of a given type therefore has the same survival probability, but the survival of each unit is treated as an independent Bernoulli event which is sampled in a Monte Carlo fashion. This procedure incorporates the uncertainty inherent in a military engagement into the results of the model. In the case of Blue force bombers, survival in the ingress segment represents survival to the at-target segment, but some units not surviving may successfully abort the mission by jettisoning their ordnance and returning to the carrier. These possibilities are modeled through the computations of separate probabilities for Bernoulli events representing success or failure of attempts to abort the mission and return to the carrier.

The inputs to the engagement model are the numbers of Blue aircraft of each type successfully launched, the numbers of each type of Orange interceptor encountered, the number of operational Orange defense units of each type, the weather condition at the target (at the time the aircraft arrives there), and the weather condition at the carrier (at the time the aircraft returns to the carrier). These values are sampled from their statistical distributions in a Monte Carlo manner. The outputs of the model are unit-specific loss figures for each type of Blue and Orange system (aircraft, defenses, and targets) over the entire mission. The model is run a sufficient number of times to generate distributions of results which reflect the uncertainty contained in the input predictions and in the outcomes of the engagements in each segment.

2.1.3 Value Model

ASTDA constructs a composite mission-achievement score (*utility*) from the results of each run of the engagement model through the use of its value model. The utility score distribution statistics are provided to the decision maker along with the other ASTDA outputs. The utility score is computed from a value model which evaluates the mission as a weighted sum of all the Blue and Orange losses during the mission. The weight assigned to each type of unit is based on the estimated impact of the loss of one unit on the achievement of the mission objectives. Thus, Blue aircraft have negative weights (losing a Blue aircraft reduces the achievement of mission objectives) and Orange aircraft, defenses and targets have positive weights (destroying Orange resources contributes to the achievement of mission objectives). The relative magnitudes of the weights indicate the relative importance of the various unit types on a linear value scale. ASTDA assumes that the values assigned to each Blue and Orange unit on this scale represent the command level value judgments within which the decision maker must work.

2.1.4 Decision Variables, System Variables, and System Parameters

ASTDA provides the decision maker with a single decision variable, the strike launch time to be chosen. It divides the strike launch window

into two to six equal intervals (depending on the width of the window), and presents all input and output information in terms of the starting point of each of these intervals. One hour intervals are employed in the current version of ASTDA, but other interval periods could be implemented.

ASTDA's input variables represent those independent characteristics of a strike that could have an impact on its outcome. There are a total of 10 input variables. Eight of the variables describe the numbers of specific Blue and Orange force units that will operate at each possible launch time. The other two describe the weather conditions at the target and the carrier at each possible launch time. The eight unit-specific input variables are grouped for display and data entry purposes into three categories -- Blue Force Readiness, Orange Air Defenses and Orange Ground Forces. Blue Force Readiness represents the numbers of three types of Blue aircraft (one fighter and two attack aircraft). Orange Air Defenses represents the numbers of two types of Orange interceptor aircraft. Orange Ground Forces describes the numbers of two types of Orange defensive system (surface-to-air missiles and anti-aircraft artillery sites) and one type of passive ground target. Each input force unit variable is described by a separate probability distribution for each possible launch time, while the weather input variables are represented simply by a probability of "good" weather at each possible strike launch time.

The output variables of ASTDA are the predictions of the engagement model. There are nine output variables, the number lost for each type of Orange or Blue system involved, and the composite value or utility score. Each output variable is represented by a probability distribution for each possible launch time.

The principal system parameters in ASTDA represent fixed factors from which the segment-to-segment survival probabilities are computed. They include:

- The one-on-one survival probabilities for each possible pairing of engaging forces,

- The proportion of total units of a given type that will be deployed against each type of opposing unit,
- The number of sequential engagements that can occur in a single mission segment between each combination of engaging units,
- The number of opposing units of each type that can be simultaneously engaged by each type of fighter aircraft, and
- The duration (in hours) of each of the mission segments.

Parameters in the first four groups each have separate values for good and bad weather. All of these parameters are inaccessible to the user.

2.1.5 Optimization and Analysis

ASTDA does not select an optimum strike time. Instead, it computes and presents its results in a way such that the decision maker can readily select an optimum strike time by choosing the strike time with the highest expected utility. However, since some decision makers may desire more detailed information than is provided by a single summary figure, ASTDA provides two additional analyses -- the sensitivity analysis and the intra-process (or loss-by-segment) analysis.

In ASTDA, each input variable represents a separate, independent factor which has a separate and distinct effect on each output variable. ASTDA's sensitivity analysis enables the effects of variations in the individual input variables on the output variables to be evaluated. This enables the decision maker to evaluate the effects that errors in the estimation of the input distributions may have on the results of the engagement. When using a sensitivity analysis the user must choose a specific strike launch time, an input variable to be varied, and one to six specific values of the input variable. For each value of the input variable ASTDA runs the engagement model at the specified strike time using the same value of the input variable each time the model is run, but sampling from the distributions it would otherwise use (for that strike time) for all the other input variables. This produces distributions of results for each output variable for each specified

value of the input variable being examined. These distributions are then statistically summarized and displayed to the user upon request.

The intraprocess analysis allows the decision maker to examine, for a specific strike launch time, the distributions of losses for both the Blue and Orange forces in each segment of the simulated missions. The user specifies a strike launch time, and ASTDA runs the engagement model with the data for that time, recording all the losses in each segment as well as the overall mission losses. It then displays losses in each segment for the Orange and Blue forces.

2.1.6 Display Features

With two exceptions, ASTDA produces simultaneous tabular and color graphic displays of the same information. Each display shows a group of related input or output variables. For the force readiness and loss data each variable in a display is represented by an uncertainty band defined by three statistics of the distribution -- the mean, the standard deviation, and a parameter called delta. The uncertainty band is a two standard deviation range around the mean that is adjusted to most nearly equalize the portions of the distributions above and below the endpoints of the represented range. The amount of offset or bias from a symmetric two standard deviation range around the mean is called delta. In tabular representation, an uncertainty band is displayed by showing the mean of the distribution and the bounds of the uncertainty band. In graphic form, the uncertainty band is drawn as a colored bar with the mean indicated by a gap in the bar. For the displays of weather predictions, the probability of good weather at each relevant time is represented as a number in a table or a point on a graph.

The two ASTDA displays which have no graphic form are those which do not display distribution data for any input or output variables. One is the display of the weights assigned to the Blue and Orange unit types by the value model. The other is a summary display of the times at which all the input forecasts were entered and the time windows covered by those forecasts.

2.1.7 Roles of Human Judgment and Heuristics

While the presentation and computation of utilities for each of the possible strike times makes available to the decision maker a simple form of optimization of strike time, the models upon which the utilities are based embody a strong set of assumptions. Only a highly restricted representation is provided for the context of the air strike mission and the context of the decision situation. Alternate ways to evaluate the results of the engagement model are not addressed, for example, in terms of exchange ratios or relative force attrition. The additive linear value function evaluates the strike mission results by considering only the losses sustained by the various Blue and Orange unit types without regard to partial damage or initial force levels. Also, the decision maker may have reason to have more confidence in some of the input variable predictions than in others, due to personnel, equipment or other considerations, and he must somehow deal with these variations in confidence in his interpretations of the model outputs. While the sensitivity and intraprocess analysis features help the decision maker to include exogeneous variables into the decision process, the identification and integration of these factors into the ASTDA input and output information is left to his judgment.

The displays of uncertainty along with expected values enable the user of ASTDA to consider the relative risks associated with the strike launch alternatives. The user is not required to focus only on the expected utility of possible actions. Although utility functions could, in principle, be constructed to incorporate the risk attitude of the decision maker, the elicitation of the relevant judgments for such constructions can be a difficult, unreliable, and time consuming process. By displaying statistical uncertainty directly to the decision maker, ASTDA allows him to make explicit consideration of the tradeoff between maximizing expected goal achievement and minimizing the risk of obtaining unacceptable results.

2.2 ROUTE PLANNING AID

Integrated Sciences Corporation (ISC) has investigated the usefulness of a variety of decision aiding concepts for the problem of planning a transit route through a field of enemy radar stations. The objective of the ISC research has been to determine the best way to allocate problem solving functions between the human and the computer. Initial work focused on evaluating the capability of the human to draw with a graphics input device the composite detection rate function of several radar sensors (Irving, et al., 1977). A principal conclusion of that work was that people could produce accurate estimates of the composite detection rate function. The estimates of detection rate functions drawn by operators were called Sketch Models.

A subsequent investigation (Walsh and Schecterman, 1978) examined alternate ways to formalize the route planning problem and various degrees of automation that could be used in search for an optimal transit route. The basic route planning problem in all cases was to define a path in terms of connected straight line segments (called path legs) with a flying speed for each leg. The goal was to maximize the value of a nonlinear utility function which depends on both the cumulative probability of detection and the quantity of fuel consumed in traversing the route. Two formalizations of the problem were considered. In one representation, all decision variables were treated as discrete, the routes being constructed by connecting adjacent points in a rectilinear grid and the flying speed for the legs being chosen from three distinct values. In the other representation, the decision variables are continuous with the routes being comprised of five legs with connecting "waypoints" located anywhere on the planning map and flying speeds for the legs taking any values between maximum and minimum limits. For each type of problem representation, three general types of decision aiding concepts were developed -- manual route planning, totally automatic route planning, and interactive route planning (called operator aided optimization, or OAO, by ISC) in which the operator directs a constrained automatic search procedure. A dynamic programming algorithm was used for the automatic and OAO search functions for the discrete version of the problem and a nonlinear programming

algorithm performed those functions for the continuous version of the problem. The main conclusions of the study were that:

- The continuous formulation of the route planning problem was more appropriate than the discrete formulation.
- The OAO-NP aiding concept (i.e., OAO with nonlinear programming) achieved the best overall problem solving performance.
- The lack of a technical education was apparently not an impediment to good performance with or without either type of aid.
- The time required to train an operator adequately to use either aid was relatively short, namely, four hours.

In the following discussion we will use the term "Route Planner" to refer to the manual and OAO aiding concepts developed by ISC to address the continuous formulation of the route planning problem. In the manual mode implemented by ISC during the experiments, the operator was only allowed to make a single guess at the best route. This corresponds to the unaided manner in which route planning is done today; it served as a baseline for comparison with the OAO concept and the fully automated concept. At the time of this writing, ISC is about to start an experiment to compare a modified version of manual planning with OAO. In the modified version, the operator will enter a route and the computer will calculate and display criterion values for the path, including cumulative utility, detection probability, and fuel consumption. The operator will optimize by iteratively seeking improved paths based on what he has learned from criterion values obtained from previously input paths.

The OAO-NP concept developed by ISC calls for the operator to make an initial guess at the best route, after which the NP algorithm iteratively modifies the route parameters (path geometry and flying speeds) to achieve the local optimum. In general, the operator must try several cycles of the process of making a guess and having it improved by the NP algorithm before he can be reasonably assured that he has determined a globally optimal path.

It is important to recognize that the decision aiding concepts developed by ISC to assist in the route planning have been oriented more toward addressing general issues of decision aid design than toward the demonstration of a comprehensive aid for an operational decision problem. The authors of the ISC documentation cited above make it clear that an operational route planning aid would have to incorporate factors (e.g., flight altitude) which they were forced to reject for the sake of experimental economy. Nevertheless, we will describe the Route Planner as it has been configured for the ISC experiments in order to indicate the extent to which existing software can be borrowed or adapted to perform route planning functions in an integrated aid. Figure 2-2 diagrams the structure of the Route Planner.

2.2.1 Target Problem

The decision aiding concepts developed by ISC are potentially applicable to a broad range of multivariate optimization problems, but to date, the system has only been applied to the problem of planning a transit route through a dense radar surveillance field. The current system requires an input file that specifies the origin and destination of the route and the location of each radar station. All radar stations are assumed to have identical detection capabilities (though in the earlier research with the Sketch Model, variations in radar detection characteristics were implemented.) The quality of a route is assumed to depend on the cumulative probability of being detected and the expected consumption of fuel, though other criteria are compatible with the aid. It is likely that the route planning decision would be made by an air operations officer. The appropriate timeframe for the route planning decision depends on the availability of information about the locations and characteristics of enemy radar stations and their capability for movement. If the radar stations are non-mobile land-based installations, route planning may be conducted days or weeks in advance of the transit mission. If the radars are ship-borne or mobile land-based units, the route planning decisions would be limited to several hours before the start of the mission. For airborne radars, it would probably be desirable to have a route planning aid that could be used in real time.

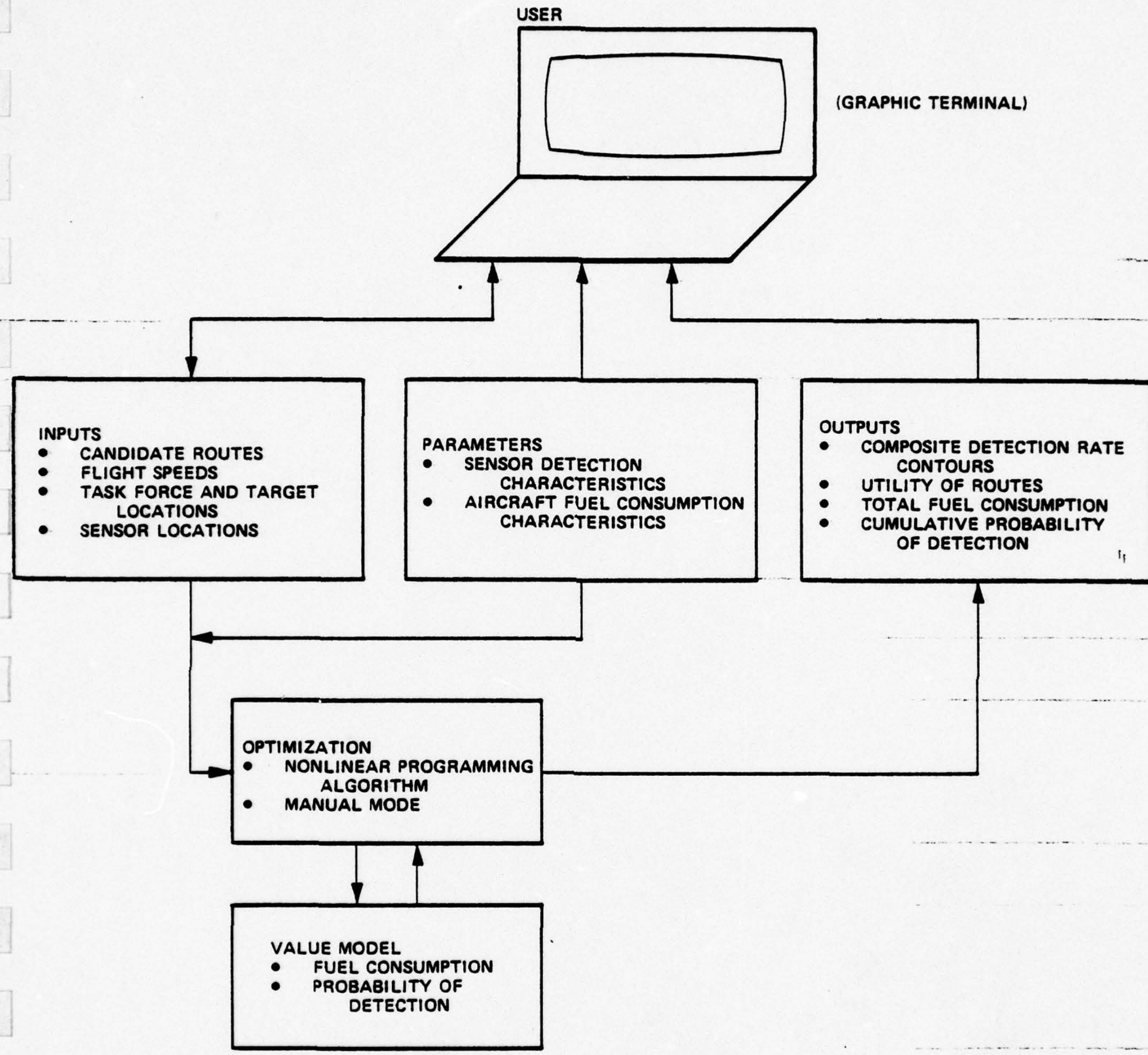

Figure 2-2. Route Planner Structure

2.2.2 Process Model

The Route Planner has no engagement model comparable to those used by the other three aids described here. It uses closed form analytic formulas to model the consumption of fuel and the cumulative probability of being detected as aircraft traverse the route from the carrier to the target. Fuel consumption is computed for each leg in the route by multiplying the length of the leg by a fuel consumption factor which is dependent on the speed chosen for that leg. The values are then summed across all the legs in that route. The cumulative probability of detection is also computed separately for each leg and then combined over all the legs. For each leg, the cumulative probability of detection is computed from an integral of the detection rate function taken over the interval of time the aircraft is traveling the leg. The time duration of a leg is calculated directly from the length of the leg and the flying speed. Uncertainty in the input data is not considered in any of the computations.

2.2.3 Value Model

Two attributes for the value of a route are currently identified in the Route Planner, cumulative detection probability and fuel consumption over the approach route. In addition to providing the user with separate information about these component route criteria, an overall route utility is defined as a nonlinear function of both criteria. In the utility function, a fuel consumption term is raised to a power that is a function of the cumulative probability of detection. The particular form of the utility function is somewhat arbitrary, with a particularly complicated formula being used to illustrate the versatility of the technique and to produce a challenging experimental task in the initial judgment of an approach route. The fuel consumption characteristics of the strike aircraft are explicit parameters of the utility function.

2.2.4 Decision Variables, System Variables, and System Parameters

The decision variables in the route planning aid are the features which define a candidate route -- the starting and ending points and flying

speed of each leg of the route. The aid defines the complete route as consisting of five legs. Since the starting and ending points of the complete route are predetermined, four points remain to be established during the decision process with each point being defined by two coordinate values. Flying speeds must also be determined for each of the five legs of the route. Consequently, a total of 13 decision variables are treated by the aid.

Since the Route Planner has not yet been configured for operational use, we can only speculate as to which variables will be accessible to the user (i.e, system variables) and which will be inaccessible (i.e., system parameters). It seems reasonable to expect the system variables to include origin and destination of the route, sensor locations and type designations (assuming that more than one type of sensor will be considered). The Route Planner automatically calculates and displays the composite detection rate function for the complete field of radar sensors. The output variables that are available to the user for each route are the utility score and cumulative fuel consumption and detection probability figures. In OAO mode, the number of iterations of the optimization algorithm is displayed. System parameters for the Route Planner presumably include the specific detection capabilities for the radar sensors and the fuel consumption characteristics of the aircraft flying the mission.

2.2.5 Optimization and Analysis

In OAO mode, the Route Planner employs a nonlinear programming algorithm to determine a local optimum for the utility criterion function by using the user-supplied candidate route as a starting point and varying the starting/ending points of the legs and the flying speeds on them. The terminal points of the legs may be located anywhere on the planning map displayed by the system. The search is iterative so that a useful result can be obtained if the search is terminated at any time. The particular algorithm that is currently implemented uses a gradient-free method that does not require the criterion function to be differentiable. In order to improve the speed of the search for a local optimum, Walsh and Schechterman (1978) have suggested that a gradient search method be developed.

In OAO mode, a trace of the "best route to date" can be retained on the graphic map display along with its various value criteria while further candidate routes are formulated and evaluated. No special analysis procedures are available just for the manual mode.

2.2.6 Display Features

The Route Planner makes extensive use of color graphic display techniques. The operations area scenario is presented in the form of a colored map with the composite or individual sensor detection rate functions displayed as iso-detection-rate contours. Different colors are used to code different detection rates. The routes are entered by the decision maker through an interactive graphics method.

2.2.7 Roles of Human Judgment and Heuristics

Human judgment is used in the operator-aided optimization mode to provide the nonlinear programming algorithm with a start in its search for a local optimum and to determine when the search should be stopped. Humans are able to process the information contained in the two-dimensional display (really a three-dimensional display projected onto two) very quickly and intuitively. The human operator can locate likely candidate routes by simply examing the composite detection contours or even the overlapping individual sensor contours. The user is, in all likelihood, applying simple visually based problem solving heuristics such as searching for the "valleys" in the composite detection field, or by seeking an "end run" around the detection field to one side or another. The optimization algorithm is unable to selectively choose promising starting routes, a task at which the human clearly excels.

2.3 EWAR

The Electronic Warfare aid (EWAR) developed by Decision-Science Associates (Pugh, Kerchner et al., 1977; Noble, Pugh, et al., 1978) assists in the development of the emission control (EMCON) plans for a task force. EWAR facilitates the process of specifying an EMCON plan and, once one has been entered, it draws upon its data base to produce estimates of the surveillance coverage the plan provides, the amount of information the plan gives away to the enemy concerning ship identity, and the portions of the frequency spectrum covered by the plan. If the user specifies potential enemy air strikes against the task force, the aid will use a deterministic engagement model to produce estimates of the effectiveness of the surveillance provided by the EMCON plan against a strike of that kind. EWAR also allows a comparison of the surveillance effectiveness and the amount of information given away across several candidate EMCON plans. The system is interactive and produces both tabular and graphic displays. The structure of the EWAR aid is diagrammed in Figure 2-3.

2.3.1 Target Problem

EWAR was designed to aid in the construction, evaluation, and comparison of alternative EMCON plans for a carrier task force. It aids in the processing and coordination of a large volume of information on sensor/platform capabilities and relationships and helps to balance the effectiveness of surveillance provided by the EMCON plan against the amount of information concerning the task force provided to the enemy. The effects of EMCON planning on communication, control, and sonar surveillance systems are not addressed by EWAR. Three roles for the use of EWAR can be distinguished -- *generation of EMCON plans* to be incorporated into the task force Op Orders, *modification of previously specified EMCON plans* to accommodate changes in task force disposition or equipment status, and *selection of an EMCON plan* on the basis of estimates of enemy plans to attack the task force. Thus, a very broad range of timeframes are appropriate for the use of EWAR. For all applications, the primary user of EWAR would be the electronic warfare (EW) officer.

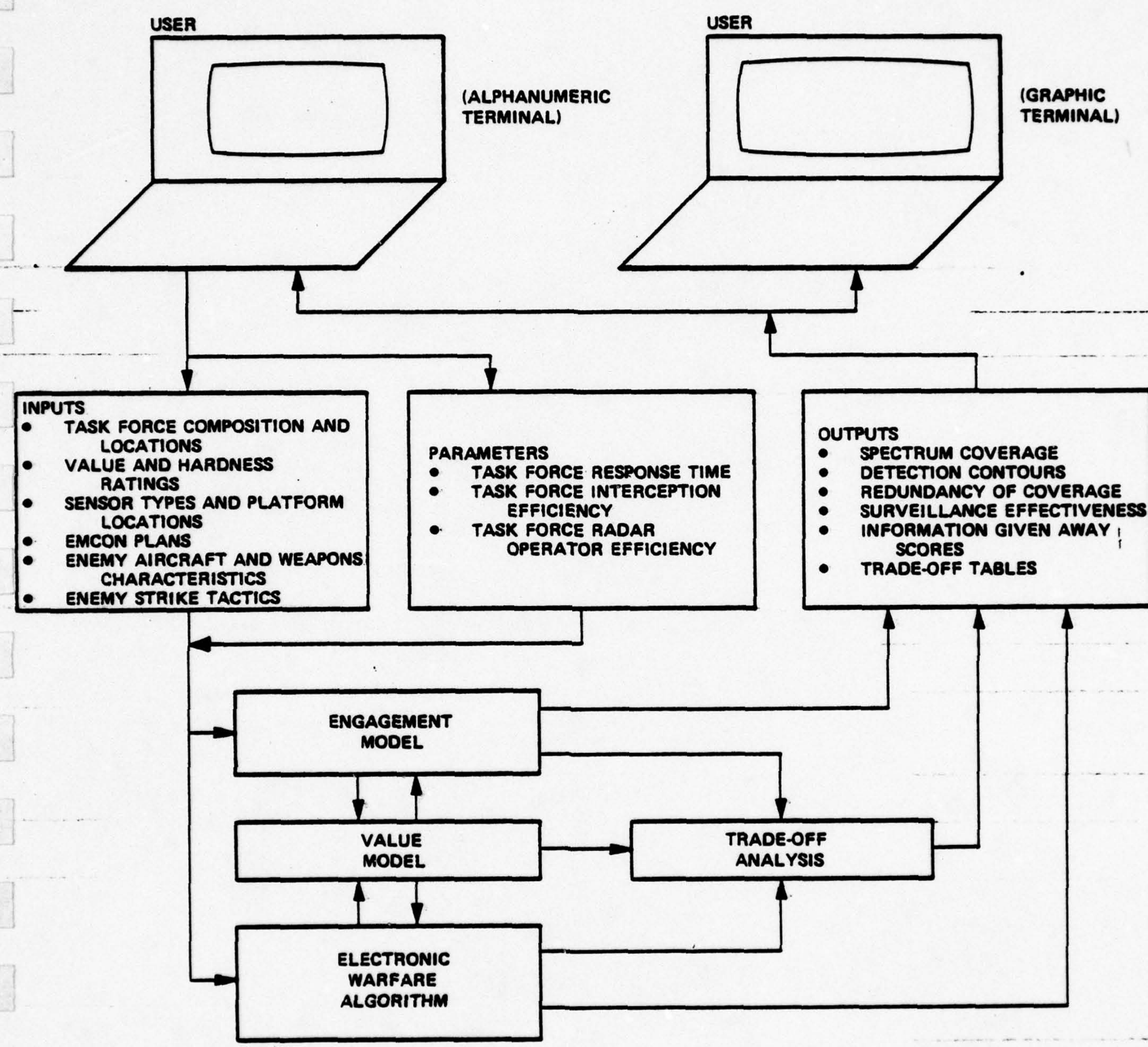

Figure 2-3. EWAR Structure

2.3.2 Process Model

EWAR incorporates a variety of models for processes associated with task force defense against enemy attacks. These include a model of the enemy's classification of task force ships based on electromagnetic emissions, several models for the enemy's allocation of strike aircraft to task force ships, a model of task force radar system performance in detecting enemy threats, and a model of the air strike engagement between enemy aircraft and the task force.

It is assumed that the enemy uses a Bayesian inference procedure to classify task force ships on the basis of electromagnetic emissions. The inference procedure is based primarily on the pattern of task force radar emissions and information about the types of ships in the task force and the types of radars carried by the ships. The model can also accommodate user-specified targeting information gained from other intelligence sources. Because the calculation of Bayesian probabilities requires a prohibitive amount of computer processing, the EWAR algorithm uses an approximation technique which gives accurate results for the situations of concern.

EWAR allows the user to allocate strike aircraft to task force ships according to any of four automatic assignment rules or by manual assignment. The automatic assignments consist of allocating strike aircraft to ships either optimally or proportionally to ship value where ship value can be based on either the actual classification of the ship or the classification derived from the Bayesian inference procedure. Optimal allocations maximize expected ship damage. They consider target value, optimal attack direction (within specified limits), penetration probability, and marginal damage for each weapon.

The EWAR model for the performance of the task force radar system determines the detection rate for a specified aircraft threat by all operating task force radars. The model considers the size and altitude of the threat, its distance from each active radar, the sea state, weather, any jamming by the enemy, and operator detection efficiency.

The EWAR model for the strike engagement represents the engagement as comprised of two sequential stages; first the strike aircraft are engaged by task force air defenses, then the attacking weapons are launched and damage is inflicted on the task force ships. Both processes are described probabilistically, but the model actually operates deterministically with the outcome of each process being defined as taking its expected value. After an approaching strike aircraft is detected, a response delay (currently 90 seconds) must occur before the aircraft can be engaged. Thereafter, the strike aircraft has a 50 percent chance of surviving each successive 125 second period. Penetrating weapons have a calculated probability of hit which is different for each weapon-ship combination. This hit probability depends on ship length and parameters which indicate the accuracy of weapon delivery. The expected damage to each ship depends on ship hardness (an input variable), quantity of weapons carried by the strike aircraft (also an input), and the expected number of hits. EWAR does not model saturation of task force defenses by large numbers of attackers.

2.3.3 Value Model

EWAR provides several measures that can be used for comparing different EMCON plans. These measures depend on user-assigned ship values. The value of each ship represents its contribution to the overall task force mission. The default assignment of ship value is in proportion to the ship's tonnage. Three different types of value score used in EWAR are a surveillance score, an information score, and a task force survival score.

The surveillance score is computed as the weighted average of penetration probabilities for three standard threats attacking the task force using an allocation of aircraft to ships that is proportional to actual ship value. The surveillance score considers only the opportunity for a strike force to launch weapons against the task force, not the damage caused by the weapons.

The information score is a measure of information denied to the enemy by a task force EMCON plan. It is computed as a multidimensional geometric comparison of the actual value of each ship and the value resulting from the way the enemy (as modeled) classifies the ship based on task force radar emissions alone.

The task force survival score is a measure of the amount of initial task force value that would survive an enemy attack. It is defined on the outputs of the EWAR strike engagement model. The engagement model determines the fractional damage to a ship from a given attack. The survival score is computed by multiplying the value of each ship by the fractional portion of the ship that survives the attack and then summing the resultant quantities over all ships in the task force. It is a measure of surveillance effectiveness, but unlike the surveillance score, it depends on the specific aircraft in the strike force, the quantities and accuracies of weapons, and the hardness of task force ships. The survival score can be computed for strikes in which the enemy is assumed to have partial or complete information about the classification of task force ships. When the enemy is modeled as having partial information, the survival score is useful in analyzing the tradeoff between denying information to the enemy and achieving effective surveillance.

2.3.4 Decision Variables, System Variables, and System Parameters

The problem which EWAR helps the EW officer address is the fundamental structure of the EMCON plan -- which emitters are to be left on and which are to be turned off. Therefore, there is no single simple decision variable, but rather a decision matrix of emitters and ships.

The EWAR system parameters which are outside the purview of the user are adjusted by the system designers to best approximate the processes being modeled. These parameters include task force response time, interception efficiency, and radar operator efficiency.

Some system variables can be changed by the user, but since they represent static properties of force resources they would not ordinarily be changed from their default values. Ship hardness belongs in this category. It represents a physical characteristic of a ship (rather than a judgmental quality) that is used to compute ship damage from specified weapon hits. In the experimental data base currently used for EWAR, ship hardness is derived from ship value. When EWAR is interfaced with a comprehensive operational data base, ship hardness will be related to empirical data on ship vulnerabilities. Other static system variables are the variables that describe the performance characteristics of enemy strike aircraft and weapons.

Various dynamic system variables describe the particular scenario for EMCON decision making. Such variables as the composition and approach direction of an anticipated strike would be routinely entered and adjusted by the EWAR user in accordance with current intelligence estimates.

2.3.5 Optimization and Analysis

While the EWAR aid does not provide for direct optimization of the on/off assignments in the EMCON plan, it does provide a method for assessing the tradeoffs between surveillance effectiveness and information given away across different plans. The EWAR engagement model computes a surveillance effectiveness score for an EMCON plan across a number of strike threats, and other portions of the aid compute an information given away value score. These two scores can be computed and saved for several EMCON plans (using a common strike threat). In the tradeoff analysis, these pairs of scores are displayed for up to ten plans simultaneously. The display indicates the relative quality of each of the plans according to the weights assigned to surveillance effectiveness and information given away, ranging from total consideration given to one criterion to total consideration given to the other. This feature provides the decision maker with a way of comparing plans given a judgment about the relative importance of the two ways to rate the EMCON plan.

2.3.6 Display Features

The majority of EWAR displays are in a tabular format only, listing information on sensors, ships, strikes, aircraft, etc. There are also several graphic displays that fall into two classes. In the first class are the displays that are map-oriented, showing the position of the ships in the task force or indicators of the geographical spread of the radar surveillance (either individual probability of detection contours, areas of redundant coverage, or combined probability of detection contours). The second class includes displays in the form of bar or line graphs and includes the tradeoff analysis line graph and the bar graph showing the portions of the radar frequency spectrum covered by an EMCON plan.

2.3.7 Roles of Human Judgment and Heuristics

EWAR draws heavily on the expertise of the user in developing and analyzing candidate EMCON plans. Although it provides no direct aid in the initial construction of plans, it presents various types of information that would be useful in the development of variations to improve a plan. Initial candidate plans come from operations manuals, knowledge of standard operations, or a higher command level. When new plans are being developed, there are several heuristics which may guide the process, notably the treatment of all emitters of a certain type in a common fashion or the treatment of all emitters on a certain ship in a common fashion.

EWAR helps the decision maker consider a tentative plan from a variety of points of view in order to select appropriate analysis options and to formulate detailed variations that might improve the plan. Displays that help the user focus on specific characteristics of EMCON plans include the combined radar coverage display, the radar frequency range coverage display, and the tabular display of ships that can be mistaken for a given ship under a given plan.

Since the aid does not evaluate EMCON plans on a single scale but by three separate measurements (surveillance effectiveness, information given away, and task force value surviving), the judgment of the decision maker is required to assess the relative importance of each type of rating. Additionally, the task force may be susceptible to several different types of enemy strikes and the user must judge the importance of relative effectiveness of different EMCON plans against the different types of strikes. Such judgments are facilitated but not obviated by the tradeoff analysis and the displays of plan characteristics.

2.4 SOC

The Strike Outcome Calculator (SOC) developed by SRI International (Rowney, Garnero and Bobick, 1977; Garnero, Bobick and Ayers, 1978; Garnero Rowney and Ketchell, 1978) aids the operations planner in estimating the consequences of alternate plans for a carrier-based air strike campaign. SOC requires the planner to formulate a detailed air strike campaign plan consisting of mission definitions, target assignments, and starting and stopping rules for contingent missions. It interfaces the plan with a prestored data base to create inputs to a campaign simulator based on a deterministic engagement model. The simulator generates campaign outcome predictions in the form of mission accomplishment statistics and overall day-by-day battle losses. As part of the course-of-action plan for the campaign simulator, the decision maker also supplies a comprehensive operation plan to be followed by the enemy. The SOC can be run either interactively or in a batch mode. It provides tables that display the course-of-action plan, simulator, output, and background and scenario data. The basic structure of SOC is illustrated in Figure 2-4.

2.4.1 Target Problem

The SOC was designed to assist in the evaluation of operations plans for carrier-based air strike campaigns for anti-air warfare, close air support, or war at sea operations. The course-of-action plans, consisting of mission assignments, strike complement designations, and day-by-day

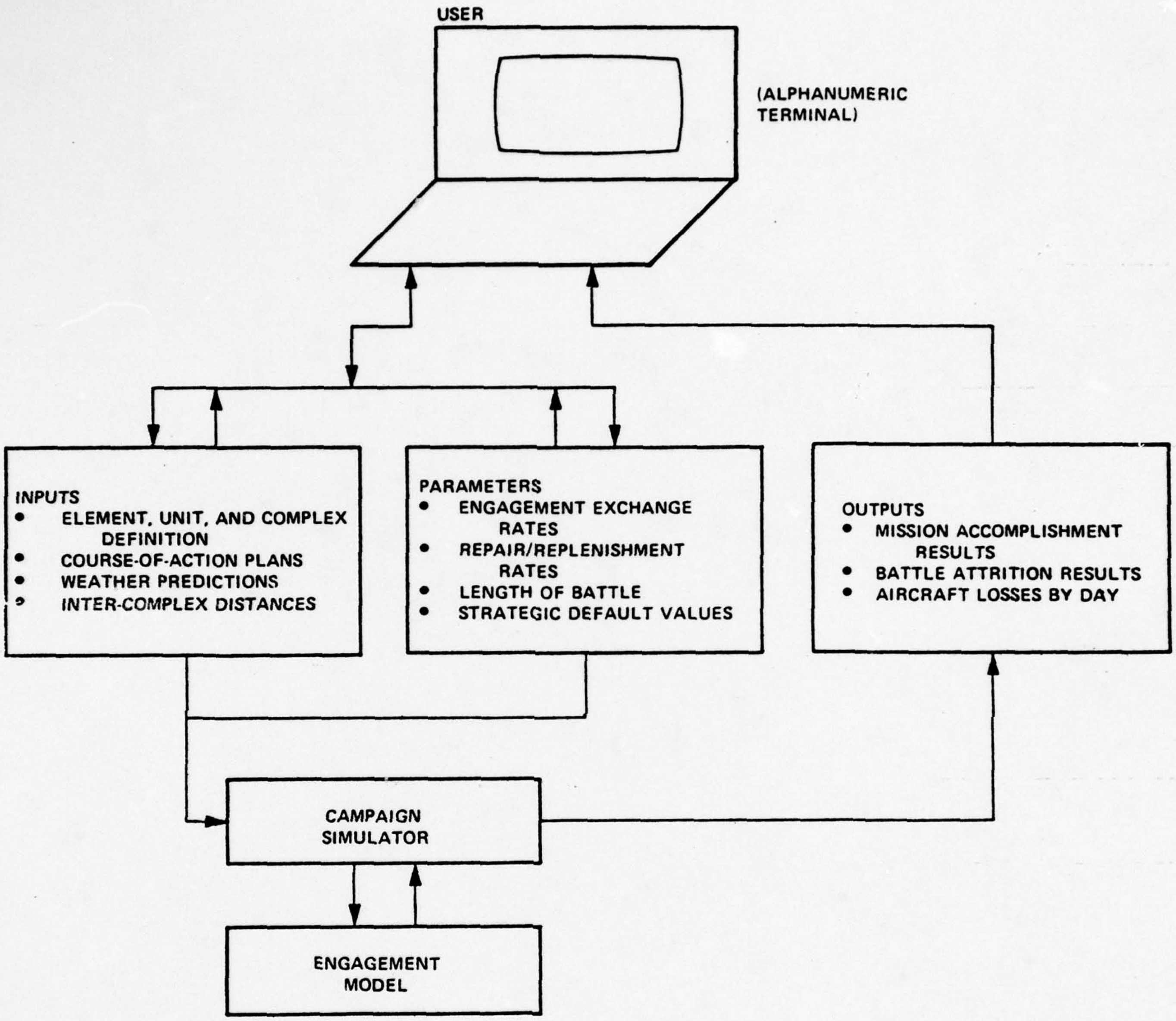

Figure 2-4. SOC Structure

starting and stopping rules for contingent or interdependent missions, are formulated by the user. SOC would be principally used during the early planning phase of the task force mission, or possibly while the task force is enroute to the area of conflict. It is assumed that only the overall objective of the campaign has been specified to the decision maker (e.g., to destroy enemy air capability by 75 percent in 20 days or less) and that, within the constraints of available resources, the planner has considerable freedom in constructing the course-of-action plans to meet these objectives.

2.4.2 Process Model

SOC employs a highly aggregated, deterministic campaign simulator to generate estimates of the results of a campaign based on a stated course-of-action plan. The mission simulator permits the representation of operations of Blue (own) force against Red (enemy) and the Red operations against the Blue task force. The Red force has the capability to launch offensive operations against the Blue task force as well as defensive operations against incoming Blue strikes. The simulator requires, as a result, a course of action plan to be created by the decision maker for Red at the same level of detail as that created for Blue. The campaign is simulated on a day-to-day basis, with each day broken into eight three-hour blocks. Everything that occurs within one of these blocks is modeled as occurring at the same time. As the start of each day, the simulator examines the course-of-action plans for Red and Blue and schedules the missions, subject to the availability of aircraft and launching platform capabilities, for each three-hour block in the day. During each block, the simulator recovers airborne aircraft waiting to land, and launches the scheduled Blue strikes against Red. The result of each strike is computed by a three-stage engagement model. The model first considers the engagement between the incoming strike force and interceptor aircraft, then the engagements between the strike force and ground defenses, and finally between the strike force and the ground targets. Each of these engagements is modeled simply by multiplying exchange rate values by the sizes of the engaging forces on each side. After all the Blue strikes in

the block have been launched, all the Red strikes against Blue are launched. At the end of each simulated day, the loss and mission accomplishment statistics for both sides are recorded. This process is repeated for each day of the campaign.

2.4.3 Value Model

Unlike the ASTDA, EWAR, and Route Planner aids, SOC makes no use of an explicit value model to aggregate or evaluate the results of the simulated campaign. However, the particular types of results that are presented in the SOC output tables constitute criteria for judging the value of a campaign. In particular, the SOC outputs enable the decision maker to observe when and with what aircraft complement each contingent mission is implemented in the simulation and how many units of each type are destroyed at each force complex and on each day of the campaign. Implicit judgments of value are also required in the establishment of several SOC inputs such as mission priorities and target assignments.

2.4.4 Decision Variables, System Variables, and System Parameters

The decision variables in SOC are the features of the Blue operations plan. The plan consists of one or more missions, each of which must be assigned a priority, an origin, a destination, starting and stopping rules (events on which the start and termination of the mission are contingent), times of launch in each day, and the type and number of units desired for the mission.

While SOC makes nearly all of its data accessible for the user for display or modification purposes, there is a distinction between those data that are intended to be estimated by the user and those that are intended to be obtained from external sources. The former data types will be considered *input variables*, the latter *parameters*.

The SOC input variables include the definitions of the elements (aircraft, target, and defensive system types), units (strike complements of

different aircraft elements), and complexes (major clusters of resources, such as a carrier task force, airfield, or supply line) for both the Red and the Blue forces. The Red operations plan, which is required by the campaign simulator, is another input variable. It is not a decision variable as is the Blue operations plan, because the decision maker obviously has no power to decide on the defensive strategy Red will use, even though he must estimate it in order to obtain outputs. Two final input variables are the day-by-day prediction of weather in the operations area and the assignment of distances (either "long" or "short") between the Red and Blue complexes. Weather is considered to be either "good" or "bad" and constant within each single day of the campaign. No estimation of uncertainty is represented for any of the input variables.

The SOC output variables are the campaign results produced by the campaign simulator. There are three types of output variables -- mission accomplishment results, battle attrition results, and aircraft expenditures. Mission accomplishment results indicate, for each mission in both the Red and Blue operations plans, the actual days on which the mission was begun and ended and the number of units launched and engaged by the opposing sides in fulfilling the mission. Battle attrition results list, for each Red and Blue complex, the number of each type of element lost and the original number of that type. The loss figures do not include damaged elements although damage is represented in the campaign simulation. Aircraft expenditure reports describe the number of sorties flown by each type of Blue and Red aircraft and the number lost to air-to-air and air-to-ground engagements for each day of the campaign. As with the input variables, there is no treatment of uncertainty in any of the output variables.

SOC parameters reflect the capabilities of various elements or complexes in the scenario. Some parameters represent weapon platform availability statistics (normal and surge sortie rates and replenishment/refuel time required), and repair and launch capabilities of the complexes. The engagement statistics or exchange rate tables which are used by the campaign

simulator engagement model constitute another set of parameters. The engagement statistics are framed in terms of losses to defending *elements* and attacking *units* expected from a single engagement. Finally, a number of campaign duration and strategy parameters, such as maximum number of days in the battle and length of time for various types of missions, must be set by the SOC user before the simulator can be run.

2.4.5 Optimization and Analysis

SOC provides no explicit optimization features, but it does contain some capabilities which enhance the comparison of alternative operations plans. The load/store features of SOC allow the user to establish and store several alternative course-of-action plans, and then reload and simulate each to compare the campaign results generated by the simulator using each different plan. The priority assignment for missions allows different forms of missions to be compared easily. Each mission must be assigned a priority, but missions with a priority of zero will never be launched. The decision maker can, therefore, enter several alternative specifications for a mission into the operations plan and sequentially test their impact on the campaign results by giving the alternative being tested a non-zero priority and all the others a zero priority.

2.4.6 Display Features

Although only tabular displays are used in SOC, it can only be run on certain types of character display terminals. SOC makes available to the user all of the input variables, parameters, and outcome variables through a set of 19 tables. Each of these can be viewed independently by the user, although when a totally new problem is being entered, the tables must be called and loaded in their numerical sequence. Update of existing values or entry of new values in a table is done by positioning a cursor to the location of the data in the table and simply entering it, overwriting whatever (if anything) was there.

2.4.7 Roles of Human Judgment and Heuristics

The judgment of the decision maker is crucial in SOC by virtue of the absence of optimization, sophisticated analysis features, or an explicit value model. While the aid determines the form of a course-of-action plan, it leaves the specification of the plan for both Blue and Red to the user, who must rely on his training and experience. In this sense, SOC is more of a tool for assessing the consequences of a camapign plan than an aid for constructing one. The evaluation of the overall campaign results produced by the campaign simulator is also relegated to the judgment of the user, since no value scale for combining the various outputs is provided by the aid.

3. GENERAL ISSUES FOR INTEGRATION

3.1 TARGET PROBLEMS

There are a variety of issues that must be addressed in designing a system that integrates a set of decision aids. The first is the determination of the range of decision problems for which the system is to be used. Primary candidate problems for the integrated system are all the problems that are addressed by the separate component aids. It is also possible that the integrated system will be able to deal with some variations, extensions, and combinations of these basic problems by exploiting some of the complementary characteristics of the component aids. In addition, new problem applications may be possible by incorporating elaborations on the component software in the integrated system. The ultimate choice of the additional decision problems to be addressed by an integrated system will be dependent largely on the cost of dealing with additional problems and on the probable usefulness of the additional capabilities.

The aids, as currently implemented, deal with the problems of planning a task force campaign and of emission control policies for that campaign, as well as the more action-oriented problems of determining an approach route and a launch time for a single air strike. Through a variety of extensions, modifications, and different combinations of the four current decision aids, many additional types of decision problems could be addressed. Some of the possibilities are:

- The ASTDA engagement model could be used to address aspects of the strike planning problem other than launch time, such as ideal strike force complement, allocation of attack aircraft to ground defenses and targets, and consequences of various mission abort rules.

- ASTDA and SOC components could be combined to deal with short sequences of interdependent strike decisions in the same operational timeframe as ASTDA. One such problem is the choice of launch times for two strikes on the same day.

- The Route Planner could be integrated with EWAR to help the user determine the relative vulnerability of the task force to enemy strikes using different approach routes.

- EWAR could be modified for application to the operational problems of determining which EMCON plan to use in a specific situation.

- SOC and EWAR could be used together to develop campaign plans that include specifications of contingencies for applying various EMCON plans.

Although it is possible to use the current, separate versions of the ODA decision aids to attack these new problems, such attempts would probably be frustrated by a variety of limitations in each aid and by incompatibilities between the aids.

It is therefore important to define the full range of problems for which the new integrated system is to offer assistance before the system is developed. A complete statement of objectives will permit identification of possible undesirable gaps in system applications. It would also permit the consideration of marginal cost-benefit issues concerning the development costs required to enable the system to deal with new problems.

3.2 PROCESS MODELS

A second integration issue relates to the nature of the processes described by the aids and the way in which those processes are modeled. Three of the four decision aids being considered -- SOC, EWAR, and ASTDA -- incorporate some type of mathematical model of the air strike engagement. The engagement models, however, are all distinctly different from one another. Although all the models ostensibly represent the same type of air strike scenario and although they employ comparable levels of detail for input and output variables, the processes are described in different ways with different variables in each

aid. These differences are partly the result of differences in orientation among the decision aids and partly the result of differences in the aid developers' concepts of the engagement process. The particular forms of the engagement models were generally secondary considerations in decision aid development with all the aid developers. Their primary objectives were to demonstrate the value of particular decision aiding techniques and the value of particular kinds of information in particular kinds of problems. We do not want these statements to be construed as casting blame or finding fault with any individual's or organization's work. We are simply stating that the development efforts were *not* oriented toward the development of the *ultimate* engagement model. Process models were needed so that the desired output data could be generated from the available input data for each of the aids, but it was not considered necessary to develop the best possible models for the exploratory study of the aiding techniques. Fairly crude process models were felt to be capable of generating sufficiently reasonable outputs for the initial evaluations of decision aid concepts. Operationally acceptable models requiring substantial development costs were justifiable only when it was clear that the resulting aid would be acceptable to the user population and enjoy extensive use.

All three of the engagement models describe attrition of force elements as a function of the numbers of all types of elements involved in the engagement. The ASTDA model represents a carrier-launched air strike against a defended ground target. It is the most elaborate of the three models because it attempts to describe the complete distribution of possible results associated with specific engagement conditions. The other two models describe only the average results that should be expected for any engagement. The EWAR model is concerned only with air strikes against a naval task force in the open sea, while the SOC model represents air strikes against both land and sea targets. The three models use different parameters from one another to describe the capabilities of force elements to inflict damage on enemy force elements and resources. The ASTDA model distinguishes

only between survival and loss of force elements while the SOC and EWAR models distinguish degrees of damage to force elements.

Although it would be desirable for an engagement model to use only observable, quantifiable data for inputs and model parameters, the engagement models in ASTDA, EWAR and SOC all require a variety of subjective estimates of the fighting capabilities of aircraft and ground defense elements. Somewhat different engagement capability estimates are required by the three models. ASTDA asks the user to estimate the probability that each adversary will survive in a specified one-on-one engagement. SOC asks the user to estimate the probability that each aircraft of one adversary will survive in an engagement with a standard grouping of the other adversary's aircraft. EWAR asks the user to estimate the capability of each task force vessel to survive enemy ordnance, i.e., the "hardness" of the ship.

One way to resolve the differences between the engagement models in the integrated aid is to develop a single engagement model that satisfies the requirements of all the decision aids. Such a model could be developed from the three existing models and could be designed to incorporate the important features of each model. Some of the necessary features of such a combined model would be that it would:

- Describe damage to force elements as well as survivals and losses.
- Be sensitive to weather conditions.
- Be exercised in either a stochastic mode to predict the complete distribution of engagement results or in a deterministic mode to predict average expected results.
- Be sensitive to the times when information about opposing force locations and motions were available to each adversary.
- Structure the engagement process in terms of sequential segments representing approach of strike force to target, engagement between strike force and interceptor force, engagement between strike force and ground defenses and targets, and return of strike force to base of origin.
- Represent strikes against both land and sea forces.

Although the Route Planner does not currently incorporate any engagement model, it is noteworthy that the combined model described above could be advantageously used in conjunction with the Route Planner. Basically, a deterministic engagement model together with a value function for engagement results could be used in place of the utility function currently used in the Route Planner. The current Route Planner evaluates a candidate route according to the fuel consumed in traversing it and the probability that a strike force that flies the route will be detected by the enemy. The route planning function in the integrated aid, on the other hand, would evaluate candidate routes in terms of the expected results of engagements initiated by those routes. In the former case, the impact on mission achievement of fuel consumption and detection by the enemy would be estimated by a speculative value model, while in the latter case the impact of the same variables would be estimated at least partly by a model of the implemented mission.

As in the development of the individual decision aids, the particular form of the engagement model in the integrated aid will be a relatively minor concern during initial aid development. The principal role of the engagement model will be to define the specific variables that are to be functionally related by the model. A plausible model will be required to enable demonstrations and experiments to be performed to provide data and judgments for the guidance of further aid development, but it will not be necessary for the model to be validated against empirical criteria until a later stage of development. Only when the data requirements of the integrated decision aid are firmly established will it be appropriate to devote an intensive effort to the development of the engagement model. As the integrated aid is developed, we should expect some fluctuations in the demands made on the engagement model, both in terms of the specific variables to be interrelated and in the levels of detail with which they are treated. But at all stages of development, some engagement model will be required to permit diagnostic exercising of the system.

3.3 VALUE MODELS

A value model is, in general, a mechanism for quantifying an individual's satisfaction or pleasure in encountering a particular

situation. For the command and control decisions of a naval task force, however, it is not so much the individual decision maker as the higher authorities who established the objectives for the task force who must be satisfied. Thus, in the present context, a value model constitutes a tool for measuring the extent to which a situation represents achievement of a set of objectives or the extent to which the situation facilitates the achievement of those objectives. ASTDA and EWAR employ value models to estimate how well the results of strike missions satisfy task force objectives. The Route Planner uses a value model to measure the degree to which a strike route facilitates an effective strike mission.

In all of these cases, values are measures of movements toward or away from ultimate goals. But it is usually difficult to judge the impact of immediate events on long-term goals, so short-term goals associated with the immediate situation are identified and used as surrogates for the long-term goals. Rather than to attempt to weigh the possible results of an air strike in terms of a detailed analysis of the relationship of those results to task force objectives, it is much more expedient and reliable to use a simple value function based on the force attrition to both adversaries involved in the strike engagement. It is even more expedient to assign values to the initial conditions of a strike engagement and thereby avoid the complexity of an engagement model, as is done in the Route Planner. However, the further removed the value model is from the variables that describe the ultimate mission objective, the more difficult it is to ensure that the value model is completely consistent with those objectives.

These two observations about value models, that values measure achievement of objectives and that value functions are often defined on intermediate, surrogate objectives rather than on long-term objectives, are important considerations when consolidating component value models. In an integrated aid, all valuations should relate to the same long-term objectives. Value assignments to short-term objectives should be made consistently and with reference to

the long-term objectives. Values assigned to different short-term objectives should reflect the relative contribution of the surrogate objectives to the long-term goals. Consequently, an integrated aid should use a single scale of value measurement. The three value models from EWAR, ASTDA, and the Route Planner can be consolidated fairly easily since they all deal with the same surrogate parameter -- force attrition in a single air strike. (The Route Planner can define values in terms of strike mission results in the manner described in Section 3.2 by using an engagement model.) However, a value model for long-term task force missions that is consistent with both the true long-term objectives and the short-term value model is more problematical. A simple force unit attrition function may not be an adequate way to represent long-term task force goals. For example, the objective of the task force may be to neutralize an air strike campaign waged by one third world nation against another, but with the stipulation that minimal damage is to be inflicted by the task force in order to avoid aggrevating a sensitive political situation. An appropriate value model for this objective would discriminate factors other than massive destruction that would lead to the termination of the air strike campaign. It would also deal in a complex way with enemy force attrition. Such a value model of long-term goals would in turn raise doubts about the validity of a value model for short-term goals that dealt only with force attrition data in single strike engagements.

This difficulty is not peculiar to task force campaign planning. In fact, it is generally the rule rather than the exception that human decision makers are ambiguous about how they move toward global goals when making decisions in contextually restricted situations. As March (1978) points out, it is often quite intelligent to behave in this way. It is often unclear to the decision maker how the outcome of the present decision situation will contribute to the achievement of global objectives, particularly when many subsequent decisions and uncertain events lie between the immediate outcome and the global objective. Furthermore, the contextual boundaries of the "local" decision often impose a restricted rationality on the situation that prevents the decision at hand from being maximized on the global and local value functions

simultaneously. The hypothetical limited warfare situation posed in the above paragraph is representative of this type of conflict between the bounded rationality of a limited decision situation (i.e., how to neutralize the aggressor nation's air campaign), which dictates maximizing the damage inflicted as the surest way to achieve the local goal, and the global objective (i.e., defusing a tense political situation) which dictates an opposite decision criterion of minimizing the damage. Even disregarding March's concern with the transience of preferences and its role in exacerbating decision makers' tendency toward global value function ambiguity (since in military situations, preferences can be considered to be externally imposed by higher command levels), the rationality of being ambiguous about global tastes is a major problem to be dealt with in constructing a value model for an integrated aid.

One possible way to solve this problem has been suggested by Pearl (1977). He argued that value models for short-term goals should be defined in terms of conditional probabilities for the achievement of the long-term goal. That is, the value of any possible immediate situation should be defined as the conditional probability that the long-term goal will eventually be achieved given that the possible situation actually occurs. With a comprehensive simulator of the campaign process, e.g., SOC, it is conceivable that sensitivities of long-term objectives to the results of single strike engagements could be systematically analyzed. A key component that is missing for this approach is a value model for the overall campaign objectives. It may be the difficulty of the task of developing such a model that accounts for the fact that the SOC is the only aid of the four considered here that does not incorporate a value model. Although it may seem plausible that the outcome of a single strike engagement could be accurately valued in terms of a linear additive function of constituent force attrition, it is much more difficult to accept that the final result of an extended task force campaign might be evaluated as a weighted sum of accumulated force losses or survivals. The objectives of task force campaigns cannot necessarily be defined in terms of an ideal level of destruction to be inflicted on the enemy and a maximum

permissilbe level of damage to be incurred by the task force. Other factors, such as preventing the enemy forces from indulging in other activities at specific times, may be major considerations in task force objectives. Considering the difficulty of quantifying long-term task force objectives, it is appropriate to expect descriptions of force attrition and combat events to be the primary outputs of a campaign planning aid and an aggregated value model to be an optional, secondary output.

3.4 DECISION VARIABLES, SYSTEM VARIABLES, AND SYSTEM PARAMETERS

The particular variables to be treated as decision variables in an integrated system are dependent upon target problems to be dealt with by the integrated aid. Ideally, the system should be designed in such a way that virtually any variable may be treated as a decision variable and subjected to the analyses and optimizations warranted by its role in the analysis. Such a design would enable new model features for the treatment of new target problems to be easily accommodated and would ensure that the aid could be applied to the maximum number of different problems.

In an integrated system, the distinction between the terms "system variables" and "system parameters" as used in the discussion of decision aids in Section 2 would be less clear. System variables referred to variables to which the aid user had fairly free access; system parameters referred to the less accessible variables. In the integrated system, all variables involved in the component process and value models will be accessible to the user, i.e., will be system variables. A data structure that would support this flexibility is described in Section 5. In this structure, data would be segregated on the basis of permanence. A background data base would contain information, like the performance characteristics of weapons and sensor platforms, that could be expected to remain constant over the course of a campaign. A scenario data base would contain transistory information, like force locations and movements, that must be supplied at the time of any specific decision. The user will be able to review and update all information in both data bases, but according to somewhat different procedures.

A number of new variables, not currently treated by any of the four separate decision aids, would have to be incorporated in the integrated system. For the sake of expedience in developing the demonstration systems, some potentially relevant variables were excluded from the component process and value models. However, as the systems move toward an operational configuration, it is important that all relevant variables be appropriately treated. For example, the ingress altitude of the strike force (which is *not* treated by the Route Planner) probably has as much impact on fuel consumption and probability of detection (and the consequent effectiveness of the strike mission) as does the flight speed of the strike force (which *is* treated by the Route Planner) for most air strike situations. In ASTDA, the probable duration of an air-to-air engagement should be considered and the planned or expected motions of sensor platforms should be considered in both route planning and in EMCON planning. Some of the variables of the separate aids must also be consolidated in order to avoid burdening the decision maker with redundant requests for data. Examples are the disparate parameters for fighting capability of force elements in ASTDA, EWAR, and SOC.

A particularly important issue to be considered concerns the treatment of uncertainty associated with data estimates for the different variables to be used in the integrated system. Most of the variables involved in the process models and value models of the separate aids refer to information for which precise objective measurement is infeasible. Variables like fighting capabilities, future weather conditions, future force readiness, and even current force locations have highly variable degrees of uncertainty. The different aids currently have different strategies for dealing with the uncertainty in their variables. SOC and EWAR assume that all uncertain variables take on their expected values. Consequently, all modeled processes can be treated as deterministic. The Route Planner assumes that the enemy sensor locations are known but treats the output variables representing detection of the strike force by the enemy as probabilistic. ASTDA offers the most comprehensive treatment of uncertainty of the candidate aids by treating weather conditions as probabilistic and by describing both input

force readiness and output force attrition in terms of statistical distributions. These differing representations of uncertainty derive from a variety of considerations ranging from expediency to general decision aiding philosophy.

Some of the major arguments against the explicit treatment of uncertainty in decision aids are:

- Parameters that quantify uncertainty are difficult to estimate and cannot be estimated reliably.
- Inclusion of uncertainty parameters generates an unmanageable quantity of information to be considered by the user of the decision aid.
- Predictions of average outputs based on average inputs are just as accurate as uncertainty incorporating predictions in most cases.
- It is virtually impossible to describe accurately the interrelations between the uncertainties associated with related variables.
- In order for any moderately complex model to relate input uncertainties to output uncertainties, it must be used in Monte Carlo fashion which tends to be costly in terms of computer time and storage requirements.
- Expressions of uncertainty associated with predictions are difficult to interpret and tend to obscure any trends that are present in the average predictions.

On the other hand, some of the major arguments in favor of the inclusion of some uncertainty measures in decision aiding systems are:

- If ranges of uncertainty do not accompany aid predictions, then it will be difficult to judge the correspondence between observed results and predicted results which is an important factor in determining the user's confidence in the aid.
- Uncertainties around average predictions are important for many decision makers since they enable consideration of the full range of likely results and the development of subsequent contingency plans (e.g., rescue operations).

- Uncertainty of results is demonstrably an important consideration for most decision makers who exhibit various degress of risk aversion.

- Uncertainty in input conditions can be an important determinant of average outputs in some significant situations. (For example, Craig, 1975, in a systematic study of deterministic and stochastic engagement models, concluded that input uncertainties significantly influence outputs when adversary forces are small or near parity.)

- People can learn to estimate probabilities reliably in many situations and may well be able, with appropriate training, to provide accurate estimates of probabilistic data involved in a task force campaign.

- Awkward assumptions and interpretations are frequently required to deal with deterministic analogs of genuinely stochastic processes.

A previous study in the ODA program has addressed the issue of whether or not information about outcome uncertainty is useful to a decision maker (Gettys, Moy, and O'Bar, 1976), but several problems in their experimental design prevented any firm conclusions from being drawn. In particular, it was not clear whether the uncertainty incorporated in the decision aids studied was effectively displayed. At the same time, it was clear that neither of the aids used in the study responded appropriately to the event of chief concern, a change in enemy intentions. At least one experimental study (Laios, 1978) has demonstrated that the display of uncertainty information can enhance decision making performance, but that study was concerned with an industrial scheduling problem that is rather remote from the task force command and control environment.

For lack of compelling evidence on either side of the uncertainty issue, it seems reasonable to take a compromise position and design an integrated system in which uncertainty is a user-controlled option. If the user chooses not to deal with uncertainty he can estimate all inputs at their average expected values and force the application of a deterministic version of any relevant process model in order to generate outputs. If he does opt

for the modeling of uncertainty, he can provide probabilities and statistical distributions for appropriate input data and then examine the results of a Monte Carlo simulation of the stochastic version of the relevant process model. Some effort would be required to ensure that the stochastic and deterministic form of all process models were really comparable. By enabling people to address a variety of task force decision problems, both with and without consideration of uncertainty, it may be possible to determine the conditions, if any, under which it is advantageous to deal explicitly with uncertainty.

3.5 OPTIMIZATION AND ANALYSIS

The only automatic optimization functions in the aids to be integrated are the dynamic programming and the nonlinear programming algorithms provided with the Route Planner. Both of these procedures constitute systematic searches for optimum values of nonlinear functions of several variables. For the particular type of optimization problem addressed by the Route Planner, it is evident that the semi-automatic algorithm of nonlinear programming is more suitable than the completely automatic algorithm of dynamic programming. However, both optimizing routines are potentially applicable to many of the problems that could be addressed by an integrated aid. For example, problems like optimizing the configuration of a strike force or the plan for emissions control are formally similar to the route planning problem. It is not yet clear from the ongoing experimentation with the Route Planner, however, whether or not any type of automatic optimization can significantly improve on the manual optimization alternative. If automatic optimization is called for, further research is required to determine the most effective ways to guide the human in his use of an optimizing algorithm. The nonlinear programming procedure in the Route Planner is capable only of finding a local optimum on a complex surface, so the ingenuity of the user is important in locating a global optimum. The user must learn to structure optimization problems in ways that will ensure that useful results will be produced within the available time. Convergence of both optimizing algorithms in the Route Planner can be fairly slow even with the relatively simple criterion

function used in that system, so serious response time problems can be expected to arise for more complicated criterion functions. By restricting the range and granularity of the search, the user can exercise considerable control over the time consumed by the search. Accordingly, it is desirable to offer assistance to the user in constructing a search that will be appropriately responsive to his needs. The system might, for example, estimate the time that will be required for a specified search and how that time requirement would be changed by alterations to the criterion function, convergence criterion, search limits, and search granularity.

The sensitivity analysis capability provided in ASTDA is also appropriate to a variety of applications in the integrated system. For variables over which the user has some control, the sensitivity analysis can be used to conduct a limited search for an optimal value of one variable at a time. In this vein, the sensitivity analysis might also be useful in determining appropriate limits to be used for a variable in a more comprehensive automated search for optimal levels of several related variables. In cases of variables for which the user's estimates are highly uncertain, the sensitivity analysis could be applied to determine the usefulness of initiating courses-of-action to reduce the uncertainty (e.g., through detailed simulation exercises or reconnaissance missions). By enabling the user to examine the covariation of any pair of input and output variables in a process model, the sensitivity analysis can also aid the user in understanding the behavior of the process model.

Additional analysis capabilities that could be useful for the integrated aid could be developed from standard statistical testing and modeling techniques. The user could be provided with procedures like the t-test and the F-test for comparisons of data involving statistical uncertainty. The technique of linear regression could help the user to analyze trends in noisy data. These and other statistical analysis tools would be especially important when process models were exercised in a stochastic mode, but some, like linear regression, could be useful even if uncertainty of input and output data

was not treated explicitly. Although no statistical analysis functions are provided in any of the aids currently under consideration, it would not be difficult to add this capability in an integrated system.

Another analysis technique that has not been exploited by the current ODA decision aids but which could be quite useful in an integrated system is war-gaming. Some aids, like ASTDA and EWAR, attribute fairly simple deterministic strategies to the enemy, an approach that could generate sub-optimal decisions in cases where the enemy has very carefully optimized his own strategy. Although the decision maker will generally be uncertain about the strategy employed by the enemy, it is inappropriate to base a decision analysis solely on the simplest or most obvious enemy plan. By representing the strategies of both adversaries in equal detail and by enabling the decision maker to analyze the enemy's decisions as well as his own, a decision aid could be developed that would plan optimal responses to the enemy's actions. By treating the adversary plans symmetrically, such an aid could be used to play out a scenario as a war-game and thus ensure thorough consideration of enemy options.

3.6 DISPLAY FEATURES

A diverse collection of display techniques are represented by each of the decision aids, including tables, graphs, and maps. Although all of these display types are appropriate for some applications in the integrated system, it is important to avoid confusing the user with arbitrary variations in display format. Standard display formats should be adopted for the new aiding system to ensure that the displays will be easily interpretable. The maps generated by EWAR and the Route Planner to display force locations and sensor detection rates should use similar coding and labeling techniques. Standard tabular and graphic formats should be established to deal with the types and quantities of available information. Display features that depend on idiosyncratic hardware capabilities should be avoided until it is clear that the relevant hardware will be available in the task force.

It is important to recognize that both the kind of information and the manner in which it is displayed are critical issues for interactive decision-aiding systems. For example, in the case of the Route Planner (in the nonlinear programming optimization mode), the time required to discover a globally optimal path is dependent on the user's ability to provide a good initial guess for the path. This is, in turn, strongly influenced by the effectiveness with which the information is displayed to the user. Accordingly, it would be worthwhile to investigate how alternate displays of information might impact man-machine system performance. For example, it might be more effective to display regions with similar detection rates through gray level or color intensity coding, rather than with contours. This alternative would require less complicated software and would generate displays more rapidly on some types of graphic display systems. Or it might be advantageous to transform detection rates into detection probabilities before displaying them. This can be accomplished simply by exponentiating each detection rate and subtracting it from unity, thus generating the probability of detection in a unit time interval. This derived value might be more meaningful to the user than the basic detection rate because it has a more direct impact on the course of the strike engagement as well as on the particular utility function currently employed.

Effective use of graphic displays is especially important in decision aiding because of the human's unique ability to process visually presented spatial information. In most cases, people can interpret and remember spatially coded information much better than equivalent verbal and numeric data. For some spatially oriented tasks, like the choice of an initial path for the Route Planner, it is apparent that humans are much more efficient than any available computer program. While it is necessary to use alphanumeric data representations for functions,such as entering and updating values, it is desirable to supplement alphanumeric displays with suitable graphic displays of the same data whenever possible. This display strategy was used in ASTDA's parallel graphic and tabular displays of the major input and output data. Supplementary graphic displays might also be usefully adopted for some of the campaign planning functions addressed by the SOC. At the same time, readability of the SOC tabular

displays might be improved by structuring the displayed information somewhat differently so that much less information would be presented in each display but more display options would be offered.

3.7 ROLES OF HUMAN JUDGMENT AND HEURISTICS

Human judgment and heuristic procedures are critical factors in any decision aiding system. The decision aid itself represents the collected judgments of the people who developed the system. In the case of value models especially, the model represents an heuristic shortcut for estimating how immediate outcomes relate to remote goals. In developing an integrated decision aiding system, however, the most critical issue regarding human judgment concerns the manner in which the system interacts with the judgment of the user. Some information processing functions are totally automated, whereas others are relegated to the user, with assistance from the system, and still others are left completely to the user. Ideally, this kind of division of labor results in an optimal allocation of responsibilities to the human and the machine with regard to their relative capabilities.

For each of the separate aids involved in the integration effort, it is the responsibility of the decision maker to recognize the relevance of an aid to any particular problem situation. This may seem to be a trivial task, since a route planning problem calls for the Route Planner, a strike timing problem calls for ASTDA, and so on. However, the matching of an aid to a problem could be quite difficult in some cases. As each of the aids are currently configured, they incorporate strong assumptions about what factors are involved in ostensibly generic decision problems. For example, in ASTDA, the consequences of a strike launch time are dependent upon the time variation of weather conditions and force readiness characteristics of each adversary. If the decision maker has the problem of choosing a time to launch an air strike but recognizes additional time varying factors of concern, such as offensive enemy actions that might occur prior to the strike, then he might be unsure about the advisability of using ASTDA for his problem. Similar dilemmas could arise with any of the other aids whenever there are factors involved in the decision that do not seem to fit the assumptions of the aid.

Even when the applicability of an aid to a problem has been determined, the current aids offer little flexibility in structuring the representation of the problem. Generally, values for input variables and parameters must be completely specified by the user before any aid outputs can be obtained. In using the SOC, for example, the user must supply all data required by 14 input tables after which he can instruct the aid to simulate the campaign described by that data and then he can examine the campaign results displayed in five output tables. The user cannot determine the level of detail for the description of the problem or of the campaign results. The SOC must be used in the same way at all times, no matter whether the user is undertaking the initial formulation of a complete campaign plan or the analysis of a single option in an established plan. The SOC, the Route Planner, ASTDA, and EWAR all offer highly refined structures into which the user must fit his problem if he is to use the aid at all.

More flexible approaches to decision aiding are possible and should be considered when designing an integrated system. For example, an aiding system could help the user to structure his decision problem through an interactive process which would select and configure appropriate models as they were identified. The Decision Structuring Aid being developed by SRI International (Merkhofer, et. al., 1977) addresses the general problem of decision structuring. It consists of a system for developing and analyzing a decision tree representing sequential (or otherwise contingent) decisions and events. It requires the user to assign values subjectively to the terminal nodes of the decision tree as defined by all possible combinations of relevant variables and options for both adversaries. However, the characterization of these terminal conditions can be complicated and because there can be a large number of such terminal nodes, the valuation task can be very difficult and the results unreliable. In order to utilize the capabilities provided by the four problem-specific aids, it is desirable to have a decision structuring tool that would help the user develop a suitably detailed problem scenario to which the available models could be applied. At the same time, it is important to develop more

flexible versions of the component process and value models in order to enable the user to define factors of interest and levels of detail with which to treat them.

4. SPECIFIC INTEGRATION PLANS

There are two general strategies that could be followed to develop an integrated decision aiding system for the task force command. One approach is to interface the separate decision aids into a system in which the separate aids work smoothly together, resulting in a system that is (hopefully) more useful for a broader class of problems than the separate aids. We will call this approach a bottom-up design. The alternative, a top-down approach, starts with a definition of global system objectives and then elaborates on those objectives until a set of detailed system specifications are obtained. The bottom-up approach ensures that the available technologies are provided to the decision maker in an efficient package; the top-down approach ensures that the basic needs of the decision maker are addressed. The two approaches are not necessarily mutually exclusive and parallel development of both may well be worthwhile.

4.1 THE BOTTOM-UP APPROACH

There are a number of ways in which the separate aids could be merged into a single system in which the individual inconsistencies and incompatabilities are resolved and the duplications of function consolidated. A key consideration is the level of effort that could be devoted to the task. Accordingly, we will describe a basic integrated system and, with respect to each part of the system, a number of optional features that deserve serious consideration.

In addition to solving the interface problems, certain new aid features should be developed as part of this effort to improve the *operational* usefulness of the integrated system. This need arises from the fact that the aids discussed above have been designed more for experimental and demonstration

purposes than for operational use. The principal deficiencies that must be remedied to improve their operational usefulness concern the specific variables incorporated in the component process and value models.

Only the first stage of a bottom-up integration will be described. It is our belief that initial development of the integrated aid should focus on the decision problems associated with planning a single air strike and that subsequent development should expand the system to address broader campaign planning problems. For this first stage of development, then, the components to be integrated will be ASTDA and the Route Planner. Many features of the first stage plan, however, are intended to facilitate later incorporation of EWAR and SOC functions. To facilitate reference to the proposed system, we will call it SCAMP-1 as the first stage version of the Strike Campaign Planning Decision Aid. The general structure of SCAMP-1 is diagrammed in Figure 4-1.

4.1.1 Target Problems

SCAMP-1 is designed to aid the user in planning all major aspects of a single air strike against a ground or sea target. Such factors as approach route, launch time, strike force complement and allocation of strike aircraft to targets, will be addressed by the aid. The user will be able to analyze tactical variables for either the offensive or defensive adversary in order to test his plans against optimal enemy plans. Attacks against naval forces in the open sea will be treated in addition to attacks against land-based installations, in order to expand the ASTDA's domain of applicability and to anticipate a system that will be compatible with EWAR and SOC. The aid is being designed to be used principally in the timeframe of from one hour to one day before the strike is actually to be launched. However, much of the data required by the aid could be supplied well before the strike decision was analyzed. In fact, the aid could be used on a continuing basis to keep track of the user's and the enemy's resources and force locations. The aid will be configured for multiple terminal access so that data can be supplied continuously by subordinate officers under the supervision of the principal decision maker.

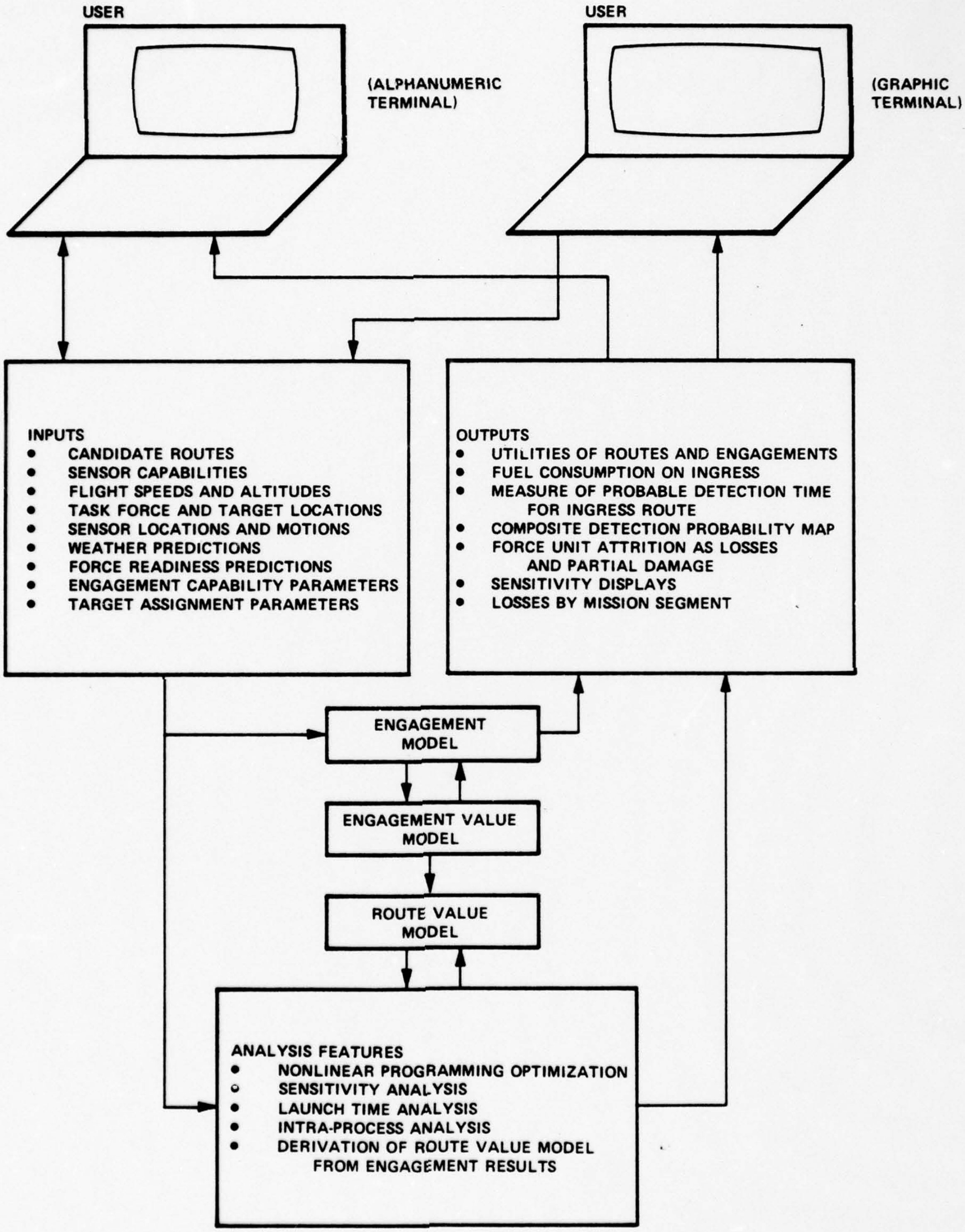

Figure 4-1. SCAMP-1 Structure

4.1.2 Process Models

The model of the strike engagement for SCAMP-1 will be an adaptation of the ASTDA engagement model. The model will be stochastic so that the uncertainty inherent in the engagement process will be included, but it will also be possible to exercise the model in a deterministic fashion by having all stochastic processes take on their expected values. Some significant modifications to the ASTDA model will be required in order to make the engagement sensitive to the features of the approach path provided by the route planning functions. The model will describe how the size of the defending interceptor force and the duration of the air-to-air engagement between the strike force and the interceptor force are influenced by the point at which the approaching strike force is detected by enemy radar. Fuel consumption by both the strike force and the interceptor force will also be factored into the engagement model to represent the relationship between fuel, fighting capability, and aircraft survival. Estimates of damage to adversary force elements will be output by the model in addition to the binary survival/destruction outputs currently provided by ASTDA. Damage estimates are needed to describe the results of air strikes against ships and, when the aid is expanded to incorporate the longer range planning functions of SOC, to describe how force readiness is affected by repair of damaged systems.

In addition to a more detailed strike engagement model, a model is needed that will describe the detection of the approaching strike force by enemy radar stations. The radar detection model in the Route Planner will form the basis for this model. In addition to being sensitive to the characteristics of the radar system and the distance between the radar and the target, the model must be sensitive to the interrelationships between the probability of detection and the numbers of targets, their sizes and altitudes, and the weather conditions in the area. In addition, it will have to model the fact that both fuel consumption rate and radar detection rate are strongly influenced by the altitude at which the strike force flies.

4.1.3 Value Models

Two separate value models will be incorporated in SCAMP-1 in order to enable candidate approach routes to be evaluated without requiring the engagement model to be run. One value model will be concerned with the valuation of engagement results and the other will deal with the approach path by itself. A linear additive model based on force unit destruction, much like the value model in ASTDA, will be used for the former purpose. However, unlike the ASTDA value model, it will assign values to fractional destruction of force units rather than to pure survival or loss. For the valuation of the approach route, the value model will use the same types of parameters as in the Route Planner but with considerable added flexibility for the functional form of the model. The two input components of the value function for the approach route will be:

(1) Probability that the strike force will be detected weighted by the time prior to reaching the target at which each possible detection point is passed, and

(2) Amount of fuel consumed during ingress.

The first component can be defined mathematically in terms of the path segment detection probabilities, where the path segments are defined either by the waypoints identified by the user (or route optimizer) or as more finely divided equally spaced segments. If there are n path segments and p_k is the probability of detection for the k^{th} segment and t_k is the time it will take to move from the middle of the k^{th} segement to the target, then the first component input to the value function is

$$\sum_{k=1}^{n} p_k t_k .$$

The above formula will replace the cumulative detection probability used in the current Route Planner to index route value. It is an improvement on the current equations because the cumulative detection probability neglects the fact that it is not just *whether* detection occurs, but *when* the detection

occurs that influences mission effectiveness. The particular function that will be used to combine the two value components will be determined through a systematic analysis of the relationship between these components and the value assigned to subsequent engagement results rather then by an arbitrary combination rule. Such an analysis should be repeated every time that engagement conditions change significantly because the influence of fuel and detection on engagement value probably depends on the sizes and relative capabilities of the adversary forces.

4.1.4 Decision Variables, System Variables, and System Parameters

There will be only minimal restrictions on the roles of the variables in the process models in SCAMP-1. The user will be provided access to all variables of conceivable interest to him. In addition to the variables included in the Route Planner and ASTDA, SCAMP-1 will deal with:

- Flight altitude of the strike force on ingress,
- Effective sizes of strike aircraft to enemy radar,
- Movement of enemy radar stations (as constant velocity vectors), and
- The effects of damage on the capabilities of force units.

Force readiness variables will be described in terms of probability distributions over possible numbers of force units, as in ASTDA. The user will have the option to let each individual variable take on its expected value. Several types of passive target will be represented to distinguish destruction probabilities and values to the strike force. Weather variables will be represented somewhat differently than in ASTDA to eliminate situations in which the binary representation of weather as either good or bad produces unrealistically large levels of uncertainty in the output distributions. In SCAMP-1, weather will be treated as a continuous variable corresponding to visibility range and uncertainty about weather as a probability distribution over visibility range. Engagement capability parameters will continue to be

defined with respect to "good" and "bad" weather conditions and linear interpolation will be used to generate parameter values for intermediate weather states.

There are several optional capabilities that should be considered if time and cost constraints permit. One possibility is to include the uncertainty in enemy radar station locations. Rather than describe station location as a latitude and longitude, these variables could be described by probability distributions that quantify the estimater's uncertainty. The primary problem in incorporating the uncertainty associated with radar locations is in the description of the impact of the uncertainty on the detection rate for a target at a fixed location. The most straightforward methods for relating detection rates to location uncertainty require prohibitive computational resources.

Another option that should be considered would allow the flight altitude to be varied over the legs of the ingress flight path. In the proposed standard configuration of SCAMP-1, the user defines a single altitude for the entire ingress flight. The suggested option would allow the decision maker to define the flight altitude for each leg of the flight path, much as flight speed is treated currently in the Route Planner. This added flexibility would increase the complexity of the displays since the decision maker would have to work with composite detection rate maps for several altitudes simultaneously. Possible ways of solving this problem are discussed below in Section 4.1.6 on Display Features.

4.1.5 Optimization and Analysis

The design for SCAMP-1 will assume that optimization of route parameters will be performed manually, although allowance will be made for eventual addition of an automatic optimization procedure. Sensitivity analyses similar to those in ASTDA will allow the user to examine the covariation of any single input variable and any single criterion variable. An ASTDA-like analysis of the relationship between launch time and engagement

results will be available with the additional possibility that different ingress flight paths may be used for different launch times (e.g., if varying weather conditions produce significant variations in radar detection rates). The intra-process analysis in ASTDA's loss-by-segment displays will also be used in SCAMP-1.

In addition, there will be new analyses in SCAMP-1 to perform functions not addressed by the other aids. The user will be able to describe and compare engagement results for several distinct sets of engagement conditions corresponding, for example, to different strike force complements and target assignment rules. This type of analysis is a straightforward extension of the launch time analysis in ASTDA. In order to improve the computational efficiency of the system, the user will be able to specify an automatic stopping rule for the sampling of simulated strike engagements. Thus, unlike ASTDA, where the number of samples is a fixed system parameter, the sample size used in SCAMP-1 may be either specified by the user as a fixed number or determined dynamically according to a set of user-specified convergence criteria.

The application of the nonlinear programming optimization algorithm to route parameters and other variables will be reserved for a later phase of SCAMP-1 development. Optimization over combinations of variables such as strike force complement or target assignments may be useful to a decision maker and could be treated mathematically in the same way as the route optimization problem. It would, however, be infeasible to use a stochastic engagement model for this type of optimization and even with a deterministic model the amount of computer time required for the procedure may be unacceptable. Incorporation of automatic optimization in the SCAMP-1 system should be contingent, in any case, on the appearance of experimental evidence that indicates that automatic optimization can reliably produce a significant improvement over manual optimization.

4.1.6 Display Features

The principal new display capabilities that will be developed for SCAMP-1 relate to the display of the combined detection rates of all enemy radar sensors. The display techniques used in the Route Planner will have to be modified to reduce display generation time and to present radar detection information in a way that will facilitate identification of an optimal flight path. In order to construct the new radar detection map, a fairly fine grid will be superimposed over the map area (say, 50 x 50 or 100 x 100). For each cell in the grid, the composite detection rate will be calculated according to the same procedure as currently used in the Route Planner except that the basic radar detection model of the Route Planner will be elaborated to incorporate several additional factors. Calculated detection rates will then be converted to detection probabilities for unit time dwell in each cell. The resulting matrix of detection probabilities will then be converted directly to a display of equal detection probability regions by collapsing the continuously varying detection rates into a few probability classes and assigning a different gray level or color intensity to each class.*

The basic bar graph display that is used in most of the ASTDA displays will be adopted for presentation of the same types of data in SCAMP-1. These displays enable the user to compare the distributions of a single output variable over several different engagement conditions or mission segments.

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*It would be interesting to compare the quality of route plans produced by people using detection rate contour maps and those using detection probability region maps.

If the user is allowed to vary the flight altitude of the strike force over the legs of the ingress path, new display techniques must be developed so that the user can examine simultaneous detection probability maps for several different flight altitudes. Two possible ways of offering several maps at one time are:

(1) Generate hard copies of each, and

(2) Generate four maps at the same time in four quadrants of the CRT screen.

By using the latter approach, the same candidate approach path could be traced on all four maps at the same time in order to help the user see the relevant tradeoffs in detection probability and altitude.

4.1.7 Roles of Human Judgment and Heuristics

Human judgment will be used in SCAMP-1 in basically the same ways it is in ASTDA and the Route Planner separately. It will continue to be necessary for the user to identify his problem, to estimate model parameters so as to represent the problem situations, and to select the analysis procedures that can help him to make a decision. However, the new display and analysis procedures should make these tasks a little easier than they are currently in ASTDA and the Route Planner.

4.2 THE TOP-DOWN APPROACH

In contrast to the above discussion of the bottom-up approach, there are relatively few details about the top-down approach that can be offered. The components of the bottom-up approach, the separate ODA decision aids, are presently available; the top-down approach must start with a systematic analysis that is yet to be undertaken. The object of the analysis must be to identify the needs of the decision maker in structuring campaign planning problems and in formulating global objectives for the campaign.

Although the SOC provides a structure for the representation of a task force campaign plan, it does not assist the user in developing the plan or, more importantly, in defining the objectives to be achieved by the plan. The first step in attacking the campaign planning task should be to define the purposes of the campaign. Purposes should be specified operationally in terms of desirable and undesirable end situations that should be encouraged or discouraged by the task force campaign. Objective situations could be described positively, for example, as the situation in which the Orange air strike campaign from ONRODA against the Grey mainland has ceased and the Orange-supported faction in Grey has not taken power; or they could be described negatively, for example, as the situation in which the major world power, Red, does not actively support Orange in the war between Orange and Grey. Once the situations that are potentially of consequence to the task force campaign have been enumerated and described at a gross level, it is necessary to add details to the situation descriptions in order to make goal satisfaction verifiable. At this point, factors such as timing of events and possible mitigating circumstances must be considered. Next, the characteristics of the elaborated objective situations must be related either deterministically or probabilistically to the variables represented in the available process models. For example, at this stage, the analysis might call for a probability distribution to describe the expected relationship between force attrition and the Orange commander's decision to cease launching air strikes against Grey. Before considering any action options, all interrelations between the objective situations should be analyzed to ensure that they are mutually exclusive and independent of one another. Finally, after considering all the aspects of the above analysis, the decision maker would assign values to each of the situations considered. The result of this procedure would be the determination of surrogate values for variables that can be related by process models to variables under the control of the decision maker.

The above goal analysis procedure is admittedly sketchy and requires considerable elaboration, but it should be clear that it represents a

significant departure from the Decision Structuring Aid (Merkhofer et al., 1977). The above procedure calls for a thorough analysis of objectives prior to any consideration of action alternatives while the Decision Structuring Aid forces the decision maker to define and analyze plausible actions before considering the value of possible results. The problem with the latter approach is that it requires the decision maker to perform a very difficult valuation in which the situation being assigned a value may have an unclear relation to the overall campaign objectives.

Development of the goal analysis approach to decision structuring will define the requirements for a campaign simulation model and the appropriate analysis capabilities to be used with the model. A somewhat elaborated version of the SOC, with a more developed engagement model, would probably suffice for the simulation model, though the specifications for the simulation should be defined only after some initial experimentation with the goal analysis in the task force planning context.

It should be noted that the goal analysis procedure is not an alternative to the Decision Structuring Aid, but rather a supplementary procedure for addressing the problem of defining a value function. The decision tree structuring components of the Decision Structuring Aid would be quite useful in a campaign planning aid, but only when values can be assigned reliably and consistently to terminal situations.

In summary, the top-down approach to an integrated decision aiding system could provide the decision maker with a tool to guide him in a top-down analysis of his decision problems. The system begins each analysis with a thorough definition of goals that are systematically related to predictable (though perhaps uncertain) results of actions that may be made by the decision maker and his adversaries. Options for action are then analyzed and contingency plans are developed. A comprehensive campaign simulation model is then exercised and, along with the value model constructed at the outset, value distributions can be derived for each string of actions, adversary responses, and uncontrolled events.

5. GENERAL SOFTWARE STRUCTURE

There are several phases in the representation of a decision problem. The decision maker must specify and describe his problem in terms of the established operations and contingency plans, the decision alternatives, and the value model involved. This can be termed the Problem Specification, or PS, phase. But the mere statement of a problem does not necessarily define what will be considered as the information needed to solve the problem. The desired solution must also be described in terms of the decision variables, decision criteria, and analysis forms to be used. This can be termed the Solution Description, or SD, phase. The description of the solution is clearly spearate from the description of the problem, yet it is also dependent on it because each type or class of decision problem has only a limited number of criteria or variables through which a solution may be defined.

The model of the real world that is used to generate the desired solution to the problem must be based on empirical data (or lacking this, informed judgments) concerning the characteristics of the processes being modeled. The creation of this empirical data base can be termed the Permanent Data Base Establishment, or PDE, phase. Each of the process models of the various aids described above, for example, requires a large number of parameter values which represent features or capabilities of weapons platforms, sensors, etc. In the case of the integrated aid, these data would include such things as maps, aircraft/ship sensor performance statistics, combat engagement statistics, or invariant tactical information. While these empirical data or judgments are obtained and entered to a decision aid independently of any specific problem or its solution, the permanent data to be used in solving a given problem are totally determined by the

PS and the SD and the process models used. PS, SD, and PDE represent conceptually distinct components of a decision aiding system, yet in the context of a specific problem they have clear logical interrelations. This suggests that a general software organization for the integrated aid can be developed in terms of the PS, SD, and PDE functions.

In each of the four separate aids, this three-part structure is present but not explicit because each aid was designed to address only one type of decision situation or problem and because the aids are currently configured more for demonstration and experimentation purposes than for operational use. Each aid provides only a fixed (though sometimes fairly exhaustive) set of decision making criteria as outputs, and since the problem type and decision criteria are hard-wired, the background data are also hard-wired, or at best very tightly constrained. No distinction is made in the separate aids among the PS, SD, and PDE functions because there is no flexibility in these functions. In the SOC and ASTDA aids, for example, all the displays can be selected from a single "menu," *whether* the displays are intended for PS, SD, or PDE purposes.

Such hard-wiring should be avoided in any complex, computer-based decision aid. Each time the integrated aid is used, a problem and a solution must be specified, and background data (if not already present) must be provided. Of course, the solution criteria possible and the background data needed will be determined by the choice of a decision-making problem. Since the type of problems to be considered by an integrated decision aid are quite varied, the *kinds* of problem description, solution, and background data that may be used by the aid must also be diverse. In any single application, not all (or perhaps not even many) of the possibilities will actually be used. The decision maker should only be required to deal with those issues relevant to his problem; the rest of the possibilities should be transparent to him. So in the integrated aid, there should be three basic functions at the highest level of the system:

(1) Problem Setup/Recall -- which consists of specifying (a) an operations scenario (e.g., who is where, with what resources, under what weather conditions), (b) a set of alternative courses-of-action, and (c) a value model for the problem. These data constitute a *Problem-Specific Data Base* (PSDB) which logically must be entered in the above order. A PSDB may be stored and recalled later for further analysis or modification.

(2) Viewing/Entering/Updating Background Data -- which consists of interfacing a user (who, in this case, may not be the decision maker) with all the background information needed by the various decision aiding models. These data form a *Permanent Data Base* (PDB).

(3) Solution Setup/Output Request -- which consists of specifying the decision criteria to be used and the output variables and/or forms of analysis desired (e.g., outcome predicitions, utility predictions, sensitivity analysis, and optimization). These requests, combined with the PSDB, will result in a particular decision aiding algorithm being selected and run (using data from PDB) and the desired results being made available to the decision maker.

This organization is diagrammed in Figure 5-1. The vertical arrows indicate control flow, and the horizontal arrows indicate logical sequences in which the information must be entered. For update/viewing, the order is irrelevant. The background data function would normally not be conducted by the decision maker (but by subordinates) and could be entirely transparent to him unless he undertook a problem for which the needed data was absent. This situation would cause an alert indicating that the calculations were being performed without all the needed data, or would force the entry of the missing information.

While certain modifications will be required to make the individual aids work synergistically on new problems, this organization can even accommodate the separate aids as they now stand. It is primarily a superstructure to be built on top of the other SCAMP software to tie it all together

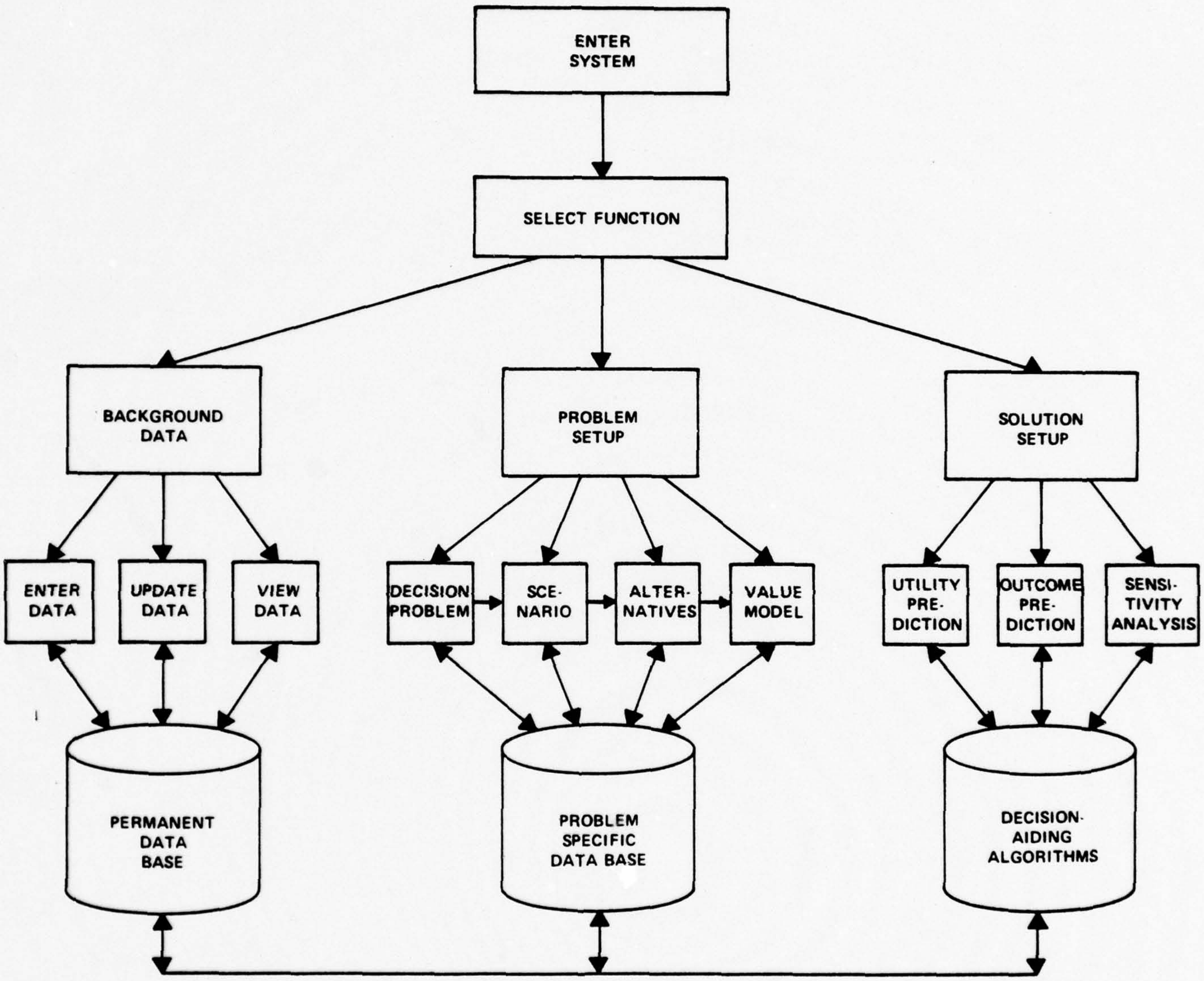

Figure 5-1. General Organization of Software for Integrated System

and to allow inclusion of new functions and programs. To clarify how this organization would appear to the user, an example user interface is provided in the appendix.

A permanent data base that is appropriate for the SCAMP system has been developed in the ODA programs (CTEC, Inc. 1976, 1977). Since the ODA Data Base represents the structure and content of the kind of Navy data bases that might be available in the coming decade, development of the integrated decision aid on that foundation should facilitate eventual implementation of the aid in the fleet. It is appropriate to make maximum use of data that is currently represented in that data base in defining the input variables and parameters for the SCAMP system.

6. CONCLUSIONS AND RECOMMENDATIONS

This report has surveyed several of the available ONR decision aiding systems that address aspects of the problems of planning air strike missions and extended naval task force campaigns. The characteristics of these aids have been described with regard to how they could potentially interface with one another, the operational completeness of the problem representations in each aid, and the decision structuring needs of the decision maker. In these descriptions, some incompatibilities among the aids were noted and suggestions were made as to how these incompatibilities could best be overcome in an integrated decision aiding system. In seeking to overcome the incompatibilities among the individual decision aids, a number of desirable attributes for the integrated system have guided our considerations:

- Consistency
  - -- Separate models for the same process should be consolidated.
  - -- Separate ways of assigning value to the same type of criteria should be reconciled in a single value model.
  - -- Values for short-term objectives should be appropriately related to long-term objectives.
  - -- Definitions of data variables should be consistent.
  - -- Arbitrary variations in display format should be avoided.
- Validity
  - -- Operationally appropriate input variables should be represented in process and value models.
  - -- Output variables should be relevant to the decision process.

-- The value model should accurately translate short-term and long-term objectives into preferences on process model outputs.

-- The structure of the process models should conform to real-world task force situations.

- Flexibility

-- It should be possible to configure parameters and options in the process models to represent all scenarios of potential interest.

-- It should be possible to tailor the value model to describe all objectives of major concern.

-- Definitions of data variables should admit representation of all realizable situation characteristics.

-- The user should be able to apply general analysis procedures to a maximum range of specific questions.

-- The aid should be compatible with the information and analysis needs and the decision making styles of all individuals who will use the system.

- Efficiency

-- Minimal information supplying tasks should be imposed on the user.

-- Minimal demands on computer resources should be made both in terms of processing time and storage requirements.

-- Displays should not be cluttered with information irrelevant to the user's interests.

- Extendibility

-- It should be possible to add new modeling capabilities, problem applications, analysis techniques, and display procedures to the aid without being forced to re-design the entire system.

- Understandability

-- The user should be able to understand exactly what information is requested of him as system inputs.

-- The user should be able to interpret system outputs in operationally meaningful terms.

-- The user should be able to recognize the domain of problem situations for which the aiding system is relevant.

-- The user should clearly understand what factors are included and what are excluded from the analyses performed by the aid.

-- The user should be able to understand all options available to him at each stage of aid implementation.

-- Effective system design should minimize the prior special training required for an individual to learn to use the system properly.

Some of these characteristics tend to be incompatible with one another (e.g., representing all relevant variables and minimizing the data input task for the user), so compromises are required. But the integrated decision aid must exhibit all of these characteristics to a reasonable degree if it is to provide an effective interface between component decision aiding functions and, at the same time, be responsive to the needs of the decision maker.

A number of general issues which differentiate decision aiding methodologies have been considered:

- Uncertainty

  -- Statistical uncertainty in modeled processes and data estimates can be treated explicitly in terms of variability measures or average conditions alone can be described.

  -- Rather than adopting either alternative alone, process models and analysis procedures should be developed that will permit the user of the aid to determine which alternative treatment of uncertainty to employ on a case-by-case basis.

- Valuation

  -- Valuation of process results can be achieved through problem-specific value models or hierarchically structured

value models can be developed to define long-term objectives and to relate them to short-term results.

-- Any value model should be considered as an optional addition to the standard presentation of predicted unvalued engagement outcomes. Problem-specific value functions should be incorporated in the integrated system with value parameters supplied at the time of the decision analysis. Research should be initiated to determine a framework for the definition and valuation of naval task force objectives.

- Optimization

  -- For most well-defined processes with associated value models, it is possible to offer mathematical optimization techniques which determine configurations of input values that produce maximum output values or to leave the search for optimum conditions to the user.

  -- The initial formulation of the integrated system should be oriented toward manual optimization procedures and experiments should be conducted to determine if significant improvements over the manual procedures can be achieved by automatic or semi-automatic optimization techniques.

- War-Gaming

  -- A decision aid can be designed to deal only with the choices to be made by a single decision maker or with the choices of both adversary decision makers in the form of a war-game.

  -- The integrated aid should be optionally operable in a war-game mode in order to ensure realistic treatment of the alternatives open to the enemy.

Underlying all of these recommended capabilities of the integrated aid is the idea that the expertise of the principal decision maker and his staff should be thoroughly incorporated into the decision process.

Two distinct approaches to aid integration are described; both should be pursued in parallel. A top-down approach addresses the problem of defining global task force objectives, relating them to results that can be modeled, then defining the model and analysis requirements at the highest level of the system to be developed. A bottom-up approach focuses on the elimination of interface problems between component decision aids to produce

an efficiently functioning system. A first stage application of this approach is described for decision problems associated with the planning of a single air strike mission. The proposed system, called Strike Campaign Planning Decision Aid-1 (SCAMP-1) is comprised principally of features from the Route Planner and ASTDA.

The general conclusions reached in this study are as follows:

- Although the four problem-specific aids developed in the ODA program exhibit effective techniques for attacking certain problems, they cannot currently be used effectively together to attack problems that overlap the domains of the separate aids because of substantial differences in process, value, and data representations.
- To provide reliable valuation estimates for the available decision aids, the decision maker requires assistance in relating immediate actions to long-term goals.
- The user of the integrated aid should be able to access and analyze sensitivities to virtually all variables represented in component process models.
- The engagement models in ASTDA, EWAR and SOC can be made compatible with one another only through development of a consolidated engagement model which could be optionally exercised in deterministic or stochastic modes.
- The value models in the Route Planner, ASTDA, and EWAR can be consolidated in a general value model defined in terms of the destruction to both adversary forces in an air strike against a land or sea based force complex.
- To develop a structure for a value model for an extended task force campaign, as represented by SOC, it is necessary to undertake a systematic analysis of the types of long term objectives typically addressed by task force campaigns.

Principal recommendations for continuing development of an integrated decision aiding system are:

- An analysis should be made of global task force objectives in diverse scenarios in order to develop a procedure for determining how the results of short-term actions influence the achievement of long-term goals.

- Further development of system requirements with respect to the construction of extended campaign plans should be postponed until initial development of both SCAMP-1 and the analysis of task force objectives are completed.

- A bottom-up approach should be applied to the development of SCAMP-1 which analyzes problems associated with the planning of a single air strike mission.

Specific features to be incorporated in SCAMP-1 should be:

(1) A model of the air strike engagement for land and sea based targets that considers the effect of time of threat-detection on defensive response, the effect of in-flight visibility on air-to-air and air-to-ground engagements, and description of force element damage along with aggregated losses and survivals;

(2) The capability to describe uncertainty in input data, process events, and output data in terms of statistical distributions or, optionally, to treat all data as fixed and processes as deterministic;

(3) A model of the detection of an air strike force by multiple radar sensors that considers characteristics of individual radars, the number of aircraft in the strike force along with their sizes and flight altitude, and weather conditions as described by in-flight visibility for the strike force;

(4) A display of combined radar effectiveness that depicts regions of roughly equal probabilities of detection in a unit time rather than contours of equal detection rates;

(5) Displays of basic results of simulated engagements in terms of a variety of measures such as damage, losses, attrition, survival, and aborts by force unit type;

(6) An optional value model for engagement results based on damage and force losses sustained by each adversary;

(7) Displays of basic approach route characteristics in terms of detection probability and fuel consumption over the legs of the path;

(8) An optional value model for the quality of a strike approach route based on fuel consumption and detection probabilities weighted by time of detection.

(9) An optional stopping rule for Monte Carlo sampling of the process model;

(10) The capability to analyze alternate strike launch times where force readiness, weather, and approach route all change with time;

(11) The capability to analyze the results of arbitrary user-specified configurations of engagement characteristics (e.g., force readiness, weather, approach route, target assignment, strike complement).

Many of the features described for SCAMP-1 anticipate later inclusion of the models and analyses of EWAR and SOC for broader issues of campaign planning. A general programming structure for the integrated aid based on component functions of permanent data base establishment, problem specification, and solution description, should facilitate all future extensions and modifications of the system.

The initial effort required to develop a working version of SCAMP-1 is the detailed design of appropriate mathematical models for the detection of a strike force by enemy radars and the engagement of adversary forces. Designing component models can be accomplished fairly quickly since the models provided by ASTDA and the Route Planner have many of the required characteristics. Subsequent implementation of SCAMP-1 as a computer program will require significant modifications to routines that can be adapted from existing programs. New software will have to be created to perform new functions that have been radically changed from other aid implementations.

APPENDIX

SAMPLE USER INTERFACE

After calling up the integrated aid, the user would initially select a type of function for the current run from an initial menu asking to:

SELECT FUNCTION TYPE:

1. UPDATE/REVIEW PERMANENT DATA BASE
2. ENTER/RECALL A DECISION PROBLEM
3. DEFINE SOLUTION/RUN MODEL
4. STOP

If the first alternative were chosen, another menu would appear listing the various background data tables in the permanent data base that were available for viewing and update. For example:

SELECT DATA FOR UPDATE/VIEWING:

1. PLATFORM AND SENSOR ATTRIBUTES
2. ENGAGEMENT STATISTICS
3. WEAPON PLATFORM AVAILABILITY
4. ELEMENT TYPES
5. MAPS
6. END FUNCTION

The data chosen would be displayed in tabular and/or graphic modes. The user would then have the option of updating entries or exiting from the menu.

As modifications or new data are entered to the PDB, the system will perform cross-checking and error-checking operations. These will prevent the entry of erroneous or unacceptable data, and will suggest or perhaps even require entry of related data. For example, if a new element type were added, say an F-18, to the element list, then the system would request that data on its engagement statistics, sortie rate, etc., be entered to other parts of the PDB.

If the second function type were selected from the initial menu instead of the first, the user would be ased to:

ENTER 'NEW' FOR NEW PROBLEM SETUP

'OLD' FOR OLD PROBLEM RECALL

If 'NEW' were entered, a name for the new problem would be requested from the user. After one was entered, he would be given a series of prompts or tables to guide the specification of an operations scenario. For expository purposes, a hypothetical problem from the ONRODA scenario (Payne and Rowney, 1975) will be used. The decision problem will be the construction of a strike complement for a single offensive strike on the third day of Blue's campaign against Orange. This choice of problem is in keeping with the suggested capabilities of SCAMP-1 as discussed above.

The first specification requested will be the selection of a map of the operations area. The user will be asked to:

<u>SELECT MAP CODE</u> - ONRODA*

* In all subsequent user-computer communications, the portion of the line underlined is typed by the computer, and that not underlined, by the user. If no portion is underlined, however, the entire line is typed by the computer.

either from a menu of maps (in the PDB) that would be presented by the system or from a manual indicating the available map names. Here, the decision-maker enters the name of the map of the ONRODA operations area. If the problem required no map, or if no appropriate maps were available in the data base, the user could simply hit a carriage-return to indicate that no map would be selected. This "not applicable" indication would be available for all sections of the scenario definition.

Next, he would be asked to define each Blue and Orange complex in the operation area. These data would be entered in a series of tables similar to the SOC complex definition tables. Each complex would be located on the map by the user. From these locations, the system would compute distances between complexes.

The user would next be asked to:

```
DEFINE BLUE ELEMENTS - KH    (CR)
                       LEAHY (CR)
                       F14   (CR)
                       A6    (CR)
                       A7    (CR)
                       F4    (CR)
                       (CR)
```

where (CR) is a carriage return.

The responses provided indicate that Kitty-Hawk class carriers, LEAHY-class support ships, and F14, A6, A7, and F4 aircraft were being used by the Blue force. Each element type entered would be checked by the system, to ensure that data concerning it were present in the PDB. If not, the user would be alerted or the element type would be disallowed.

Then each element type would be assigned to a complex with an indication of the maximum number present. It will be assumed that Blue has only one complex designated CTF (for Carrier Task Force). The system would

prompt the user:

FOR ELEMENT 'KH' INDICATE COMPLEX AND MAXIMUM NUMBER AVAILABLE - CTF, 2

FOR ELEMENT 'F14' INDICATE COMPLEX AND MAXIMUM NUMBER AVAILABLE - CTF, 20

and so on. Similar element definitions and assignments would be requested for the Orange force. As a final part of the scenario, the user will be asked to:

SPECIFY TIME FRAME OF INTEREST

BEGINNING HOUR AND BEGINNING DAY - 600,1

ENDING HOUR AND ENDING DAY - 240,30

and to

SPECIFY TIME-STEP (IN HOURS) - 1

This establishes the entire campaign as the time domain of potential interest. This will allow the current scenario to be specified once for the entire campaign, and then merely "recalled" every time a new decision problem is encountered.

All of the above information would then be stored as the operations scenario part of the PSDB under the name supplied at the beginning of the function. If, at the beginning, the decision maker had responded "old" in order to recall a previously created scenario, the information previously stored under the stated name would be recalled. He would then be given an opportunity to review the scenario and update parts of it, or to proceed directly to the next part of the PS function, the specification of a decision variable and a set of alternatives.

Since virtually every variable in the system is available to the decision maker as a decision variable, the selection of a decision variable cannot be made from any simple list or menu. Rather, the choice will be made through a multi-level selection procedure. At the most general level, the user will be asked to choose the type of the decision variable.

SELECT DECISION VARIABLE TYPE

1. OPERATIONS PLAN
2. UNIT DEFINITIONS
3. TIME OF ACTION
4. STRIKE ROUTE
5. PDB ITEMS

These five categories cover the range of decision variables possible. Depending on the type chosen, additional lists will be presented to refine the category. For the present problem, the second item, UNIT DEFINITIONS, would be chosen. A subsequent list would allow the user to choose the name of the specific Blue or Orange unit to be considered. Here, a Blue unit named Alpha would be selected indicating that the decision variable for this problem was to be the composition of a Blue air unit referred to as Alpha.

Next, the system will take the decision maker through the iterative specification of decision alternatives. The construction of an alternative requires specifying values for all the input variables required by the process model. At the very least, the decision variable must take on different values in each of the alternatives. Other input variables may be identical or different across alternatives, depending on a variety of considerations. For example, if the decision variable was of the time-of-action type, then different estimates of the weather conditions, Blue readiness, and Orange

readiness would be required for each alternative, since each alternative represents a different point in time.

The system would direct the creation of an alternative by first requesting a value for the decision variable, then proceeding through all the other input variables. The complete specification of an alternative requires the input of:

- Course of action plans for both Blue and Orange
- Definitions of Blue and Orange units
- Ingress routes between complexes for each Blue and Orange mission-type
- Predictions of weather conditions at each complex
- Estimates of Blue and Orange readiness at each complex

More detailed description of the variables required is impossible without a complete specification of the process model to be used in the integrated aid. Throughout the specification of alternatives, the user would be able easily to indicate, say by hitting a return key without entering any data, that the data requested is the same as the data in the previous alternative (obviously this option would be unavailable in the construction of the first alternative). The user could also specify the data to be the same as in alternative "j" through some convention, such as entering "#j." These features would greatly facilitate the construction of alternatives.

Once the alternatives had all been created, the user would have the option of defining a value model. Since there are several different forms which the decision maker might wish to employ for the value model, if he chooses to implement a value model, the system will first ask him to:

SELECT DESIRED FORM FOR VALUE MODEL

1. DIRECT ENTRY
2. DYNAMICALLY CONSTRUCTED
3. AGGREGATED-LOSSES

Once a form was chosen, the system would help construct the value model and elect parameter values for it. As discussed in Section 3.3 previously, value models can be constructed in at least three different ways. The most limited perspective is provided by a direct specification of a utility function by a decision maker who has a precise, unambiguous and explicit goal in mind for the specific decision problem at hand. By selecting the first form listed above, the user could choose to create a utility function himself. This utility function could be entered as any function dependent on one or more of the process model output variables.

At the other extreme, the broadest perspective can be provided by developing a value model which relates the outcome(s) of the current decision situation to the set of global objectives for the overall campaign. This form of value model can be requested by selecting the second item in the above list. The construction of this type of value model requires a two-step procedure in which the decision maker first defines the overall campaign objectives and then defines the different kinds of ways in which these goals or objectives may be met. The campaign goals would be elected through a language of objectives in which military objectives can be stated, focusing on such concepts as "destroying," "restraining," "limiting," "preventing," and "seizing." Then, the decision maker would be asked to describe deterministic or probabilistic relationships between possible force configurations and the stated objectives. The system then uses the engagement simulator to assess the sensitivity of each of these "final states" to each of the output variables and calculates importance weights for each of them based on this analysis. These weights would then be used as coefficients in a utility function, constructed

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by the system, through which the results of the current decision problem would be evaluated. This value model will then have been dynamically constructed by using the process model to balance the current problem's results against the user's global objectives.

An intermediate course, represented by the last item in the above list, is to evaluate the results of the specific decision situation in terms of the aggregated damage and destruction to both the Blue and Orange forces. In this problem specific form of the value model, the decision maker is evaluating the immediate outcome in terms of his overall losses relative to those of the enemy without any consideration for optimizing the results with regard to long-term objectives. After the user selected this form, the system would elicit tradeoff values from the user for each of the Red and Blue element types. These values would be used as coefficients in a linear value function based solely on the number of each Red and Blue unit destroyed or damaged. The user would be asked to:

SPECIFY VALUE OF 'KH' ELEMENT - 100

SPECIFY VALUE OF 'LEAHY' ELEMENT - 10

SPECIFY VALUE OF 'F14' ELEMENT - 6

and so on. He would similarly be asked to specify values for each of the Orange elements. The primary difference between this "aggregated-loss" form of the value model and the "directly entered" form is that in the latter the user is not constrained to consider all the output variables from the process model, nor to an additive linear function relating them. In the directly-entered form, he may use only some of the output variables in the value function and he may relate them in complex functional forms.

Once the value model has been specified, the decision variables, alternatives, and value model will be saved along with the scenario description under the name given to the problem as the complete PSDB.

If the third function type (RUN MODEL/OBTAIN OUTPUT) were selected from the initial list, the system would first check to see if a decision problem had been entered to the system during the current run. If none had, it would ask the decision maker to supply the name of a problem that had been previously created and entered. If that problem did not exist or was incompletely specified, the system would abort the function and force the execution of the PS function.

Once a problem has been entered or recalled, the user would be asked to choose the types of engagement statistics to be collected by the process model for each of the element-specific output variables. These output variables will be displayed to the user after the model is run in terms of the various statistics chosen. The user will be asked to:

SELECT ENGAGEMENT DATA DESIRED

1. ATTRITION
2. LOSSES
3. EXCHANGE RATIOS

and perhaps others. One, two, or even all three of the statistics could be chosen.

The system would then ask the user to:

SELECT ACTION

1. RUN SIMULATOR
2. RUN SENSITIVITY ANALYSIS
3. RUN OPTIMIZER
4. ENTER WAR-GAME MODE
5. END FUNCTION

and possibly others. If the simulator (process model) were run, the system would use the data in the PSDB to form inputs to the model and to identify the additional data needed from the PDB. If the data needed from the PDB were found to be missing or erroneous, the decision maker would be notified and given the option of aborting the run or having the model use default estimates of the bad data. Once all the inputs were formed, the model would then be exercised for each alternative in the PSDB.

When the runs were completed, the decision maker would be asked to select output variables for display from a list containing all the output variables. As with the inputs, an exact list of the outputs cannot be given without a detailed specification of the process model, but the list would include overall utilities and some detailed mission achievement results. When a specific Orange or Blue element was selected for display, it would be displayed according to each of the statistics selected by the user before the model was run. For example, if the only statistic chosen was "attrition" and the user requested a display of the F14 output variable, the system would present the process model's estimate of the F14 attrition that would obtain in strikes launched with each alternative configuration of the Alpha unit. Once the user has viewed all the output variables of interest, he could return to the SELECT ACTION list and try a different analysis feature or he could end the function.

When the END FUNCTION option is selected from the SELECT ACTION list, the system returns the user to the original SELECT FUNCTION menu. When a request to STOP is entered from that menu, the system checks to see if there is an unsaved version of an old or new decision problem in the PSDB. If there is, it gives the user the option of saving it. This would also be done if, upon returning to the SELECT FUNCTION menu, the ENTER/RECALL DECISION PROBLEM function were selected again.

Within this kind of organization, the existing display features of the ASTDA, SOC, EWAR, and ROUTE PLANNER aids could even be maintained as they are. The new software would largely consist of table-driven algorithms to identify the permitted displays or tables at various points in the program, to identify the data necessary for processing to continue, and to monitor the PDB and PSDB to ensure that no step begins or proceeds without the required data.

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